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Resources Use Efficiency in Agriculture

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Preface

Soil, water, energy, nutrients, solar radiation, and air are important natural resources needed for agriculture and to sustain the life of all living organisms on the planet. The overexploitation of the infinitive resources by humans is an alarming issue for the farming and scientific community, policymakers, and administrators to manage them efficiently to sustain food, nutrition, water, environmental and economic security. The scientific management of natural resources in agriculture to enhance use efficiency for a sustainable future is a need of an hour. This book is concentrated on the management decision, questions and answers on the agronomic problems, soil health and nutrient problems, climate change, to make the production system more efficient and sustainable. The application and management of inputs as per the need with right amount, right time, right way and from the right source helps to save the inputs *viz.*; water, nutrients, energy, soil, and enhance the efficiency of natural resources to improve the responses of crop yield for economic importance.

The book is also focused on an efficient management of problems in crop production techniques aimed toward the soil and environmental sustainability. The function of the effective utilization of water, nutrient, soil, agri-wastes, solar radiation, nutrients, and other inputs. The book covers the modern ways of resource management through biotechnology, nanomaterials, waste recycling, and precision agriculture. The quality of soil and environment, and conservation of natural resources are essential for the future generations. The book has deeply touched the water-limited agriculture, hence a wide description on the role of water in the agronomy of agricultural production system. Nitrogen and phosphorus are the major elements for plant life whose growth is directly linked with its availability for them. Therefore, their effectual nutrient management is vital for survival and the productivity and sustainability of agroecosystem. Along with it, the book also highlighted the efficient capturing and harvesting of solar radiation in crop plants by using the physiological basis of crop production.

The effective utilization of animal and farm wastes through proper recycling *via* composting, anaerobic decomposition, gasification, and insect-driven insect degradation is a viable strategy in the direction of increasing resource use efficiency and quality food production. In this regard, the authors broadly explained the management practices of raw manure by recycling it into more effective forms through composting and vermicomposting to improve biological stabilization.

Pesticides have become an integral part of modern agriculture to control the diverse pest and diseases to protect the crop from their economic damage. The threats concomitant with pesticidal use in contemporary agriculture from the perspective of human health, environment, soil, and food security is a serious concern of immediate action. By considering the facts, the authors deeply described the biopesticides, organic farming, and tillage practices for efficient crop production sustainably.

The zinc (Zn) and iron (Fe) deficiency is an emerging problem affecting billions of people annually worldwide. Therefore, it becomes important to enhance their concentration in food crops to fight with their deficiency. Therefore, the biofortification of cereals (e.g. rice, wheat) with Fe during growth period is a vibrant, profitable, and sustainable technology to enhance the Zn and Fe content and their bioavailability in grains to combat the malnutrition.

The book has presented the agronomy as an intricate and integrative subject at the road map of several disciplines such as soil science, crop ecology, biotechnology, horticulture, soil and water conservation, water management, and plant physiology, which tends to greater attention on providing quantitative answers to specific problems. The authors nicely presented research findings and their view on all the common aspects of crop management and productivity through efficient resource management with pertinent examples of different crops ranging from herbaceous/annual crops such as sugarcane, nutrient management in rice, etc. to woody/perennial crops like almond and olive under the situation of water scarcity and climate change, fruit crops in rainfed hillslopes through reducing soil and water erosion, and silvopastoral system.

The editors fastidiously discussed the advanced notion for dealing the agricultural productivity per unit of resource use for agricultural and ecological sustainability. Overall, the above-discussed issues must need to safeguard to the efficient resource management for sustaining agricultural production for global population outbreak. A science-oriented approach *vis-a-vis* an emphasis on a healthy ecosystem approaches in agriculture and efficient utilization of natural resources has been presented at length. The information gathered from this book will be helpful in the understanding of the fundamentals of resource management for agricultural and environmental benefits.

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Contents

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Ram Swaroop Meena is an Assistant Professor at the Department of Agronomy, I.Ag. Scs., BHU, Varanasi (UP). Awarded a Raman Research Fellowship by the MHRD, GOI, he completed his postdoctoral research on soil carbon sequestration under World Food Prize, 2020 Laureate Prof. Rattan Lal, Director, C-MASC, Columbus, USA. Dr. Meena has published more than 100 research and review papers, 50 book chapters and 17 books at national and international level. He has worked as an expert for the NCERT, MHRD, GOI. He has more than 10 years of research and teaching experience, and currently working on three externally funded projects (DST, MHRD, ICAR).

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Waste Recycling for the Eco-friendly Input Use Efficiency in Agriculture and Livestock Feeding

1

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Abstract

The increasing competition for available resources and inefficient use of those limited resources necessitates the need to improve the use of available resources. If these inefficacies are not corrected, the resource-poor farmers, mainly living in developing countries will be most affected. Yet these resource farmers contribute immensely for food production in developing countries. Smallholder farmers must be proactive and learn to adopt new strategies that can assist them in continuing farming with maximum use of limited agricultural resources and even wastes in agriculture. Several methods are available to improve the use of agricultural wastes, including non-agronomic benefits. Furthermore, we suggest the integration of waste resources, such as from both the trilogy of human–animal–crop wastes. Similarly, inexpensive techniques are encouraged among the farmers, including composting and vermicomposting of human–crop–animal wastes and/or slaughterhouse/abattoir wastes, biocharing of crop and animal wastes as various means of recycling/recovering nutrients in the soil system. Furthermore, the deployment of fungi could also improve the resource use efficiency through mushroom growth and sales, crop residue fermentation to enhance its feed value. Livestock farmers facing nutritional problems can apply microbes through fermentation to reduce antinutritional factors (lignin, tannins) in plants, and improve the safety of kitchen and dairy waste before feeding. Alternatively, farmers are encouraged to raise micro livestock (rabbits, snails, and grasscutters) on their farm to improve the use of resources. On a large scale, nitrogen and phosphorus recovery from cow urine, slurry, human feces, and fermentation of phytate rich plants with phytate on industrial scales is recommended. This chapter aims to provide insight into the methods by which farmers and industries, especially those in developing countries, can improve their available resources for agricuture and as livestock feeds.

Keywords

Biochar · Biogas · Microlivestock · Nutrient recovery · Resource use efficiency · Smallholders · Waste recycling

Abbreviations

C	Carbon
Ca	Calcium
CEC	Cation exchange capacity
CH_4	Methane
CN	Carbon nitrogen
CO_2	Carbon dioxide
Fe	Iron
GHGs	Greenhouse gases
ha	Hectare
K	Potassium
kg	Kilogram
mg g^{-1}	Milligram per gram
mg l^{-1}	Milligram per liter
Mg	Magnesium
Mn	Manganese
N	Nitrogen/nitrogenous
N_2O	Nitrous oxide
NH_3	Ammonia
NUE	Nutrient use efficiency
P	Phosphorus
RUE	Resource use efficiency
t ha^{-1}	Tonne per hectare
Tg	Teragrams
TKN	Kjeldahl N
Zn	Zinc

1.1 Introduction

Globally, the livelihood of billions of people depends on the agricultural industry. It employs over 1.3 billion people worldwide and contributes to the lives of 0.6 billion smallholder farmers (Thornton 2010). This indicates that it is an industry that arguably generates more means of livelihood and services to humanity than any other industry worldwide. In the agricultural sector (crop, livestock, forestry, processing, and packaging industries), smallholder farmers are key players in food availability and security. Over 0.57 billion farms are available universally, and most of them are small and family-operated, often having less than 2 ha (hectare) producing about 75% of world's agricultural lands (Lowder et al. 2016). About 2.5 billion smallholder farmers depend on natural resources to contribute to food availability and security (Rockstrom et al. 2017). These smallholder farmers, in hundreds of millions, primarily feed more than a billion world's poor people, mainly residing in Africa and Asia (Herrero et al. 2009; Kumar et al. 2017). Due to negative environmental impacts (from nitrogenous (N) and phosphatic (P) fertilizers), water scarcity, depletion of some nonrenewable inputs, slowness in land expansion, and competition from other industries, agriculture systems are confronted with the problem of produce from available resource bases without encroaching into new ones. This calls for the need to change strategies from current farming practice, such that there is an improvement in practices and total efficiency of resources employed in agriculture-based industry (Adegbeye et al. 2020).

Land, water, and nutrients are essential resources on which agriculture owes its function and existence. Efficient use of these resources while providing access to food produced characterizes a good agricultural system. Resource(s) use efficiency (RUE) may be referred to as benefits/improved benefits that could be derived from each unit of input. Inefficiency in resource utilization occurs in the livestock and agro-food processing industry through excessive usage and wastage. To improve the efficiency of available resources, there is a need to improve nutrient use efficiency (NUE) by reducing the excessive use of synthetic fertilizer and improving the fertilizing value of animal manure. Furthermore, there is a need to recover and recycle N and P from wastewater, human and animal waste, as well as improve the quality of wastewater to improve its irrigation value.

Since the 1990s, increasing productivity has been associated with improved input use efficiency (Ramankutty et al. 2018). Additionally, overall global increases in agricultural output have shifted towards enhanced efficiency-based improvement from the previous input-based increment (Fuglie and Wang 2012). Improving the use of available resources by resource-poor farmers could increase the output per input. As such, a multi-user system that allows a circular use of resources for crop and livestock production will ensure that agricultural resources are judiciously used. However, for quick and permanent adoption, such a system should not be alien to the farmer in developing countries; rather, it should improve their current practices. This "indigenous-knowledge upgrading" approach will be farmer-friendly and afford them the privilege of relating to the system. An alteration in management may seek to integrate crop and livestock production systems, etc. Similarly, other processes such as product processing, anaerobic fermentation, composting, vermicomposting, irrigating with wastewater, upgrading manure fertilizing value, and insect farming can be associated. The overview of resource improving techniques for resource-poor farmers to enhance agricultural efficiency through reuse and recycling of nutrients of farming systems is presented in Fig. 1.1.

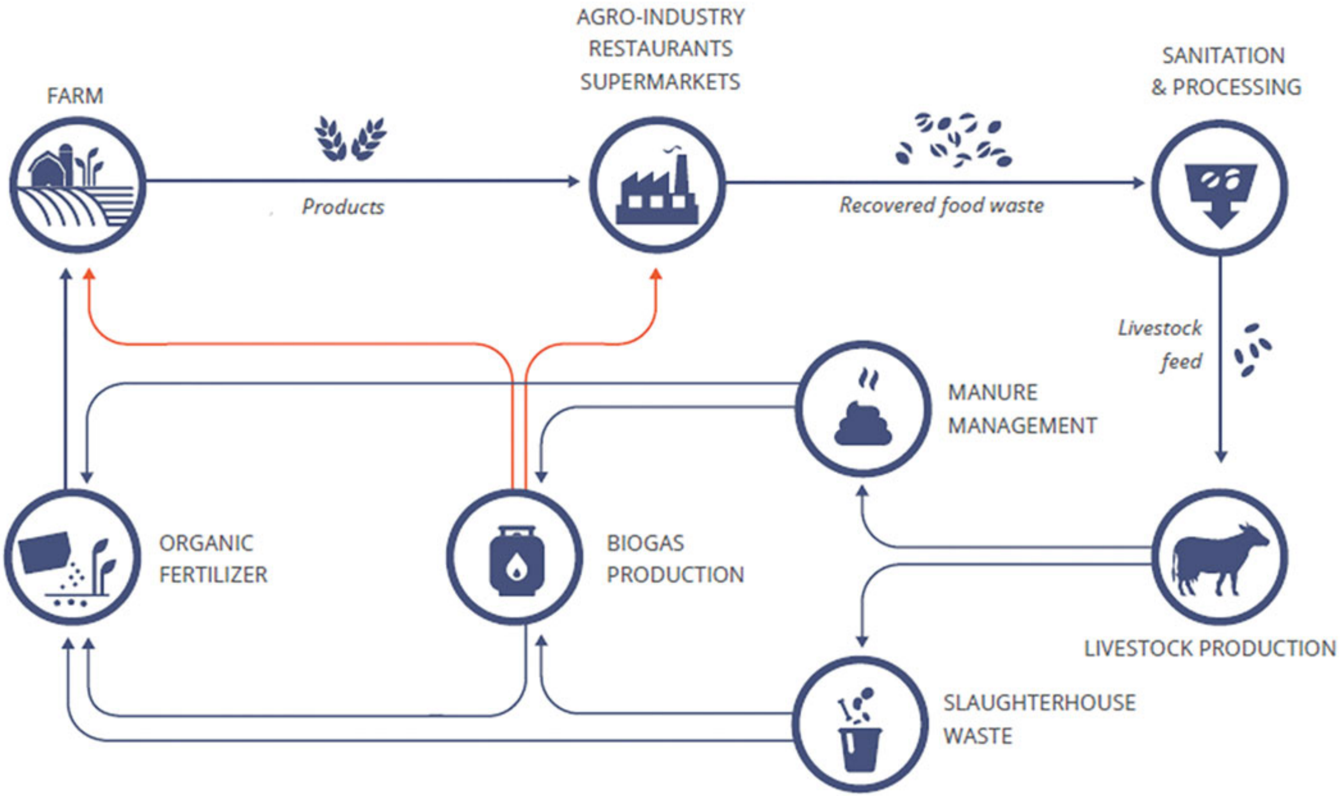

Fig. 1.1 Overview of improving the resource use efficiency (Adopted from FAO 2019)

1.2 Waste Resources Integration

Modern-day farming system models emphasize specializing agriculture such as livestock or cropping alone. This has led to uncoupling of nutrient cycle flow between both systems resulting in increasing waste in the agricultural system (Varma et al. 2017; Kakraliya et al. 2017a, b). Wastes in agrarian systems and agri-food industries are becoming valuable resources due to the essential elements in them that are important to crop and livestock. Integrating the farming system with livestock system is a crucial solution, with low nutrient input and efficiency (Sutton et al. 2013). Such crop–livestock integration signifies practical step in improving resource use (Rufino et al. 2009). It represents a means to increase output for every used input and potential to derive maximum economic yield per unit of water applied or crop planted (Singh et al. 2011). Assimilating livestock, crop, and agri-food industry wastes offer the opportunity to circulate the nutrients that could lead to a more efficient farming system.

1.2.1 Crop–Livestock System

Integrating diverse nutrient flows by linking animal wastes with cropping systems could be a means to achieve NUE (Adegbeye et al. 2020). Increasing the use of these waste resources is advantageous for resource-poor farmers, whose access to inputs such as inorganic fertilizer, feed, and large land size is limited (Thornton et al. 2018). The livestock system represents a means of gathering nutrients from the surroundings and agronomic-agroforestry systems and converting them to milk, meat, and manure (Meena et al. 2020a, b). The milk, meat, and egg represent how nutrients are "pulled" out of the agricultural system, while manure and wastewater represent the means of returning nutrients to the cropping system and the pathways for coupling/integrating livestock and crop system. Livestock offers multi-benefits to crop system such that instead of conserving crop residues for soil fertility, it could be fed to livestock consequently adding more fertilizer value to the crop residue in the form of feces/manure. Integrating agricultural farm systems is more resource-based than location-based. It connects agronomic and agroindustry associated resources like wastewater, manure, and crop residue with crop and livestock systems, to ensure exchanges even when they are spatially separated (Adegbeye et al. 2020).

1.2.2 Human Wastes

The human need to return part of the nutrients pulled from the agronomic and livestock systems. This is because many of the nutrients mined through agronomic and livestock systems are primarily by humans. Therefore, integrating crop–livestock systems and human wastes such as human excreta, kitchen, restaurant, and grocery waste can improve NUE. Yearly, many teragrams (Tg) of N and P are lost in human wastes, and many find their ways into the water bodies. Most of these nutrients lost are obtained from crop and livestock products consumed by humans. Consequently, linking the agricultural system with human waste resources could result in improved crop–livestock–human nutrient recycling. Coupling crop–livestock–human ensures that wastes such as manure, wastewater, kitchen waste, and human feces are recycled to valuable non-edible quality products such as organic fertilizer and bioenergy used to generate cooking fuel and electricity for humans and livestock.

1.2.3 Rural/Peri-urban Approach

Intensifying crop–livestock integration flows and practices outside the rural setting can bring about system efficiency and resilience (Stark et al. 2018). Specialization and intensification occur in peri-urban areas. Linking animal farmers with crop farmers can ensure that animal feces are disposed of as manure, and this will ensure cleaner and environment-friendly agriculture waste disposal method (Roessler et al. 2016; Yadav et al. 2020). For instance, biocharing, composting, vermicomposting, processing of livestock and microlivestock manure, biodigester output, and other agroindustry wastes can allow agriculture to achieve higher RUE in rural and peri-urban areas from both input and output sides. On the input end, higher output is obtained per input, and on the output end, nutrients in waste from other agricultural production systems are recycled and used on crop fields. Therefore, by modifying agricultural production and management systems through integration of livestock system with the agronomic system, on-farm interaction of crop residues and manure could bring about more efficiency by exploiting nutrient resources (Fig. 1.2) (Notenbaert et al. 2009).

1.3 Improving the Use of Agricultural Wastes

1.3.1 Insect

Insects are economically important biological resources in agriculture. They can function as producers (honey), pollinators, and pests. As a matter of interest, these insects can grow on dead woods, manure or feces, and many organic materials, which suggest that they are excellent decomposers. Due to this ability, the insect is playing and will increasingly play a key role in high-quality waste recycling. Insects can convert high energy and fibrous wastes to high-quality protein, making it a promising protein alternative in livestock production. They have a high feed conversion efficiency of waste to animal protein (Looy et al. 2013) and could produce 1 kg (kilogram) insect biomass from 2 kg substrate (Collavo et al. 2005) at low cost and breeding space (Makkar et al. 2014), with lower emissions compared to composting methods (Mertenat et al. 2019). The role of an insect in RUE is based on its ability to use inedible human waste to produce organic material of high-value protein and energy within small confinement. Insects could turn part of the roughly 1.6 billion

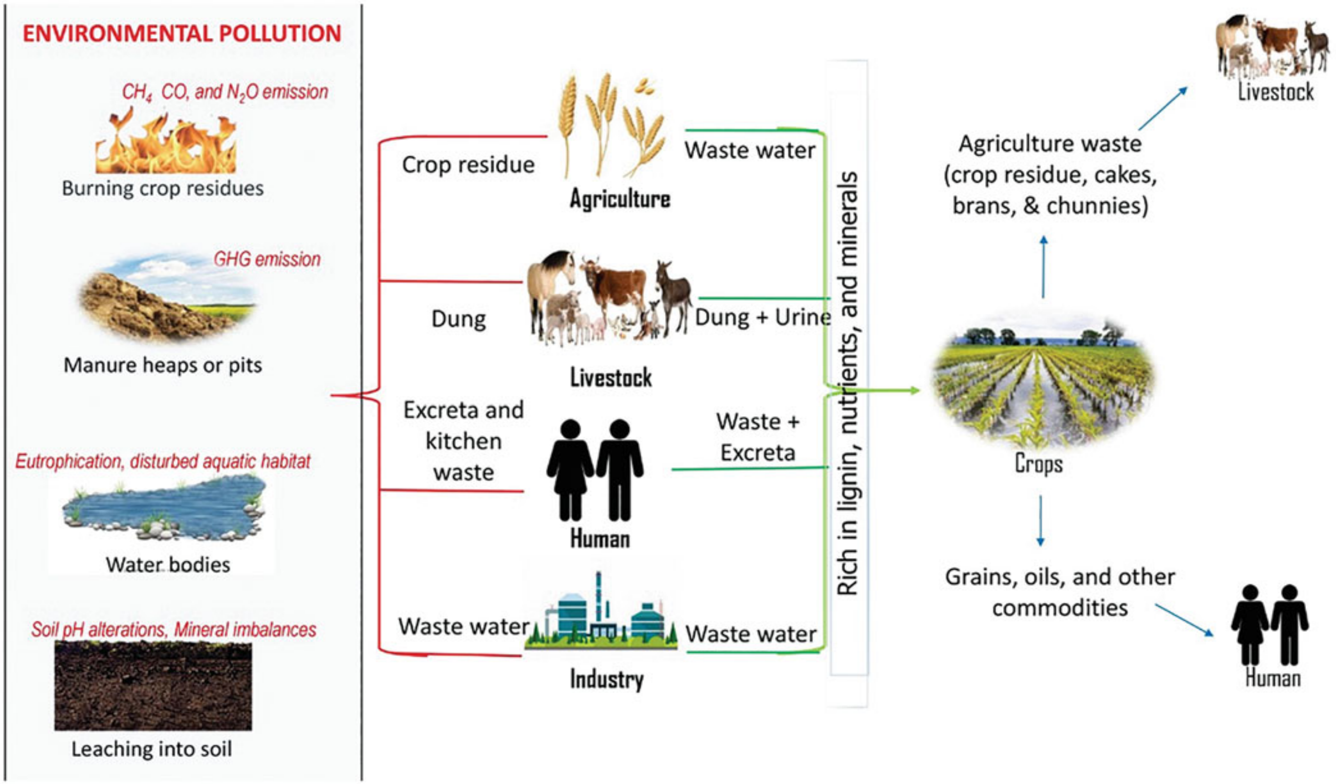

Fig. 1.2 Integration of waste resources

tons of agricultural produce being wasted yearly to high-quality protein (FAO 2013). The aim of using insects to recycle agricultural, kitchen waste and manure is to breakdown organic matter for the growth of insect larvae or fly, while the remaining may be used as organic fertilizer.

Several insects such as mealworms (*Tenebrio molitor*), house fly (*Musca domestica*), and black soldier fly (*Hermetia illucens*) are being grown on agricultural wastes; with a biodegradation potential in a range of 54–81% (Nyakeri et al. 2016). Insect larvae can be grown on brewer's waste, the solid phase of pig manure, semi-digested grass (Liu et al. 2018), and fecal sludge (Nyakeri et al. 2016). Besides, they can survive on abattoir waste, food waste, human feces, fruits and vegetables (Lalander et al. 2019; Cappellozza et al. 2019), and waragi waste (Dobermann et al. 2019). Furthermore, due to the presence of volatile solids and N content, insects can proliferate on grape (*Vitis vinifera*) and potato (*Solanum tuberosum*) peels (Barragán-Fonseca et al. 2018), rice (*Oryza sativa*) and wheat (*Triticum aestivum*) straw (Manurung et al. 2016; Gao et al. 2019), cassava (*Manihot esculenta*) peels (Supriyatna et al. 2016), mushroom waste (Cai et al. 2019), and coconut (*Cocos nucifera*) endosperm waste with soybean (*Glycine max*) curd residue (Mohd-Noor et al. 2016).

These cultivated insects are rich in unsaturated fatty acids and essential amino acids like methionine (17.62 mg g^{-1}) (milligram per gram) and lysine (19.78 mg g^{-1}) content sufficient to meet human and animal needs, but are missing in many kinds of cereal and plant-based protein sources (Azagoh et al. 2016; Cappellozza et al. 2019). Maize (*Zea mays*) straw is typically low in protein and fat, but is high in fiber, which is mostly indigestible for livestock. However, black solider fly grown on *Aspergillus oryzae* fermented maize straws yielded insect protein that is low in saturated fatty acid, high in mono and unsaturated fatty acid, and having 41.76, 30.55, and 8.24% crude protein, crude fiber, and crude ash, respectively (Gao et al. 2019). Various studies on the use of insects in livestock have shown positive results. The replacement of fishmeal with 60–100% black soldier larvae in the diet of guinea fowl improved its juiciness, texture, flavor, and acceptability (Wallace et al. 2018). Also, yellow mealworm larvae added at 50 and 100 g kg^{-1} improved feed intake, weight gain, body weight and had a positive effect on carcass traits (Biasato et al. 2017), while defatted black soldier flies added at 5 and 10% of soybean meal improved live weight, an average daily gain of broilers (Dabbou et al. 2018). This shows that biodegrading crop residue with insect leads to the production of high valued protein, which is a means of increasing the nutrient usage in agriculture.

Apart from the potential for animal protein, the remaining biodegraded and bio converted inedible human waste can be used as organic fertilizer. For instance, the biodegraded substrate left after the growth of larvae of the house fly and black soldier fly was found to be rich in NPK with similarity to China-based standard organic fertilizer (NY525-2012) (Bloukounon-Goubalan et al. 2019; Gao et al. 2019). Other studies showed that when such substrate leftover is used as fertilizer, they improved the germination index of Chinese cabbage by 65.7% (Cai et al. 2019). This implies that the insect leftover is usually rich in a nutrient that could be used as an alternative soil improver. For other uses, the biodegraded waste produced from insect farming can be anaerobically digested for biogas to generate electrical or cooking energy. Thus, food waste could first be converted to food and feed by the insect before being used for biogas production and the biodigester waste used for organic fertilizer.

1.3.2 Biogas

Biogas production from wastes can play a vital role in the waste management system. It could serve as the value addition wing of the waste management sector. Agricultural wastes are used as landfills and for mulching or manure, which sometimes trigger greenhouse gases (GHGs) and non-GHGs emission in both aerobic and anaerobic conditions. Biogas production represents an anaerobic microbial bioconversion of organic material into energy that could be used for cooking or electricity. During anaerobic digestion, biogases contain methane (CH_4) gas, which could have various fuel applications. Generating energy from wastes offers the opportunity to improve the efficiency of organic matters in the agricultural system. For example, a 20–100 kg of dairy cattle feces in a biodigester system can power biogas stove for up to 3.5–10 h and biogas lamp for10–25 h (National Biogas Program 2008). Apart from the benefit of renewable energy, biogas, the solid digestate from biogas plants could be used as fertilizer due to its nutrient enrichment. Adding the anaerobic digestate as 60% of total fertilizer used on maize plot had an NUE similar to 60% of inorganic fertilizer and higher than 100% inorganic fertilizer (Moya et al. 2019). Similarly, instead of using manure directly as fertilizer, the farmer can first bio-digest to reduce the nutrient load in feces and the resulting residue could be used as organic fertilizer. One tonne of manure could be used to produce an energy value of 100 to 125-kWh (Burton and Turner 2003). Therefore, on large farms, such manure could generate electricity or heat energy for brooding. Furthermore, it will reduce the cost of running the generator and decrease the bills paid to electrical companies. If legally permitted in the country, individuals can be selling biomethane gas on a small-scale if they could successfully compress the gas under pressure. For instance, biogas plants existing in Indian and Pakistan can produce CH_4 gases that are 98% pure, store them in cylinders, which is then used to fuel gasoline-based auto-rickshaws and diesel engines (Ilyas 2006; Kapdi et al. 2006). Biogas could also be used as a renewable fuel instead of nonrenewable fluid, commonly used in rural areas. Farmers from countries in Asia and Africa operating crop–livestock systems can use their waste resources to generate energy for cooking instead of firewood.

The potential of energy in crop residues is enormous. From the annual agricultural residues and livestock manure, up to 3,30,000 tons of fertilizers and 1.97×10^9 m^3 $year^{-1}$ CH_4 can be produced, which has the electrical energy capable of replacing 39% of annual energy consumption in Greece (Vlyssides et al. 2015). Besides animal manure, human waste can also be used to generate biogas, and the digestate can be used as organic fertilizer. The digestate of human feces subjected to anaerobic digestion had 877-milligram (mg) liter $(l)^{-1}$ total N and 42 mg l^{-1} total

P. This indicates that anaerobic digestion could be used to recover nutrient from human feces and the digestate could be used for planting to enhance NUE.

To enhance biogas yield from lignocellulolytic wastes, fungal, chemical, thermal, and mechanical pretreatment of biogas substrate has shown positive results (Olugbemide et al. 2019; Abudi et al. 2019). For example, seven days substrate pretreatment with 2% sodium hydroxide (NaOH) decreased lignin by 48.2% and increased CH_4 yield by 407.1%, and the biogas production was completed in 24 h compared to untreated materials that required 168 h for its biogas production (Shah and Ullah 2019). This implies that pretreatment of lignocellulolytic material and crop waste before digestion could lead to increased biogas production and decreased production time (Fig. 1.3).

1.4 Wastewater

Water supply will increasingly become a global issue with the possibility of about three and a half billion humans experiencing a different form of water scarcity that could be economic or physical (WRI World Resources Institute 2019). This will be particularly challenging for agriculture as agriculture is the biggest user of freshwater and contributes significantly to freshwater eutrophication globally (Nasr et al. 2015). Treating and recycling wastewater are some ways by which agricultural water scarcity can be managed. Enormous potential exists in deriving more value per unit of water through integrated and higher value production systems (CAWMA 2007). The need to improve water use is high in the tropics due to its dependence on green water as its primary source is agricultural water (Rockström et al. 1999). It is foreseen that only 5% of future grains increase will come from rain-based farming areas, while the majority will be from irrigation-based farming areas (Taimeh 2013). Therefore, in such a condition, irrigation with wastewater could be valuable for developing countries facing one or more forms of water scarcity.

Wastewater consists of nutrients that cause environmental pollution or enter into different water bodies, reducing the quality of available and accessible water. Agroindustry/processing companies are the main culprits in wastewater generation and livestock production systems characterized by low water productivity (Blümmel et al. 2015). Water management could be used for preserving, restoring the ecosystem through integrating livestock and aquaculture systems (CAWMA 2007). Managing wastewater can get more products and value from the same water, and with this, the resource-poor can benefit from the water through the crop, aquaculture, livestock, and mixed systems, improving water productivity (CAWMA 2007).

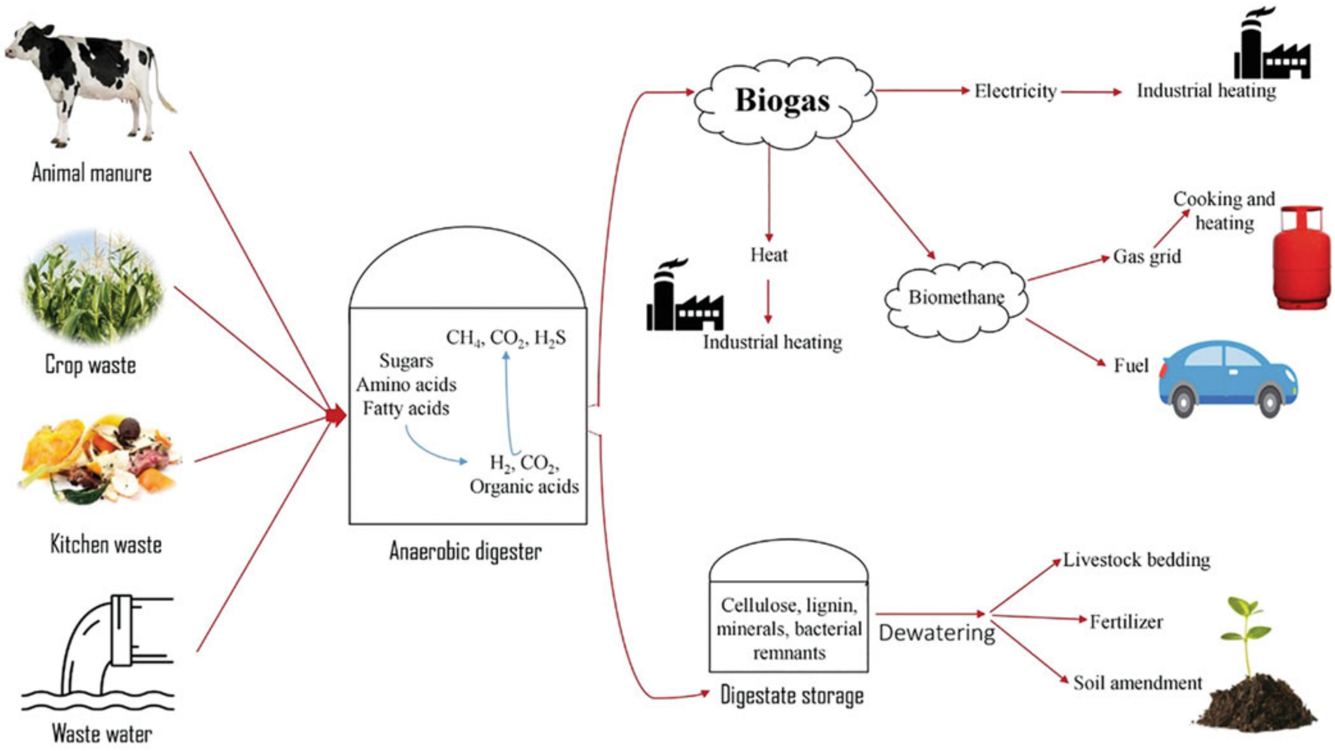

Fig. 1.3 Biogas production to improve the resource use efficiency

1.4.1 Productive Use of Wastewater from the Cassava Processing Industry

Water demand is outstripping water supply in low- to middle-income countries with fast population growth. Competition for water in agriculture and other sectors is leads to environmental stress and socio-economic tension (FAO 2011). Wastewater of such industries can be reused instead of disposing into rivers to pollute the hydrosphere and aquatic habitats. Wastewater from starch industry contains quite a large amount of nutrients; as such, microorganisms can recover part of the nutrients in the starch for protein-rich microbial biomass that can be used to feed livestock. Cassava processing industries produce a large amount of nutrient-rich water. Storing this cassava flour processing or cassava starch extract in large tank permit sedimentations of high-starch paste known as cassava dregs. Such dregs can be fed to ruminants as corn replacements. A report showed that the replacement of corn with cassava dreg increased the concentration of eicosenoic and α-linolenic acids and had a positive effect on the unsaturated fatty acid and flavor (Cardoso et al. 2019). These cassava dregs could be stored during the season of abundance and kept for dry season when forages are scare and could be used during fattening. Another way of improving wastewater use is through microbial growth. Cultivating edible fungi (*A. oryzae* CBS 819.72 and *Rhizopus oryzae* CCUG 28958) on wastewater recovered 48–77% of the nutrients, generated protein-rich biomass at a rate of 7.83–49.13 g l^{-1} of starch wastewater (Souza Filho et al. 2019). The remaining wastewater could be used in aquaculture, piggery, or irrigating field crops.

1.4.2 Wastewater from the Livestock

The piggery production system in the tropics requires the use of large volumes of water. This is because of the relatively high temperature in the tropics, which requires that pigs find means of cooling their temperature. However, pigs do not have sweat glands; therefore, wallows are provided for cooling. An expensive alternative to wallows will be the use of the air conditioner in the piggery. Also, the pigpen must be washed daily to maintain hygiene, which requires a large volume of water. This wastewater could ideally be used for irrigation. However, the risk of contaminating crop yield with food-borne pathogens during irrigation means that efforts should be made to reduce the pathogenic contamination level of livestock wastewater before it is used for irrigation. In Brazil, swine production takes about 15-l water animal^{-1} day^{-1} (Velho et al. 2012), which infer that thousands of liters of water will be wasted on large farms daily. Creating a synergy between pig farmers and crop farmers can improve water reusability, especially in the dry season, where water is scarce and could encourage all-year-round farming. Although wastewater contains high organic matter concentration and nutrients, it contains a lot of pathogenic microbes. Management practices could improve the microbial quality and decrease the nutrient content in the wastewater before reuse. Velho et al. (2012) reported that piggery water collected from maturation pond and kept in a stabilization reservoir for about 320 days showed that the total P, total Kjeldahl N (TKN), biochemical oxygen demand, and *Escherichia coli* decreased by 68, 77, 85, and 99%, respectively. The reduction may be associated with the proliferation of flora–fauna community (microbes and algae), decreasing the available substrate or precipitation of P into calcium (Ca)-phosphate complex. Partial water treatment through the method before it applies to irrigation could improve water use efficiency. However, care must be taken while using only wastewater as the source of water for crop irrigation to avoid soil salinity and oil solidity. Therefore, recovered wastewater could be mixed with fresh water from rivers or streams. This will place less demand for clean water, and less agroindustry related wastewater will be pushed into water bodies.

1.5 Nutrient Recovery/Recycling Methods

About 5–30% of livestock's total nutrient intake is retained, while others are excreted, resulting in low efficiency of nutrients, primarily N and P (Teenstra et al. 2015). These excretions have implications on surface and underground water, aquatic organisms, air quality, global warming, etc.; therefore, recovering these nutrients is essential. Low and declining soil fertility is one of the agricultural intensification challenges in Africa (Vanlauwe et al. 2017). This results in soil nutrient mining and land expansion by farmers that cannot afford inorganic fertilizer. In contrast, livestock intensification increases the quantity of manure produced, resulting in excess N, P, and K balances in agriculture (Vu et al. 2012; Abdulkadir et al. 2013).

Manure use has not been optimally exploited as a local nutrient source among resource-poor farmers (Sutton et al. 2013; Meena et al. 2018). Applying manure for soil amendment rather than indiscriminate disposal is a way to ensure nutrient cycling and soil fertility. This practice helps to return up to 80% of the nutrients extracted by crops back into the soil system in sub-Saharan Africa (Stangel 1995). However, the manure's direct use leads to nutrient losses (ammonization, leaching, runoffs etc.). Developing a closed nutrient cycling system in agriculture through the efficient use of stored manure could increase crop yields (consequently their by-products—as feed) and farm output (Thornton et al. 2018; Meena et al. 2019). Improving manure processing will lead to optimal nutrient benefits derivable from manure and increase the fertilizer equivalence value. Vermicomposting, composting, and anaerobic digestion represent one of the ways to utilize nutrient in the manure properly. Soil nutrient amendment with manure contributes to greater fertilizer use efficiency (Fig. 1.4) (Nigussie et al. 2015).

1.5.1 Composting and Vermicomposting

Direct application of manure on the field causes nutrient losses and pathogenic contaminations. Pathogenic contamination like *Salmonella* spp. and *Escherichia*

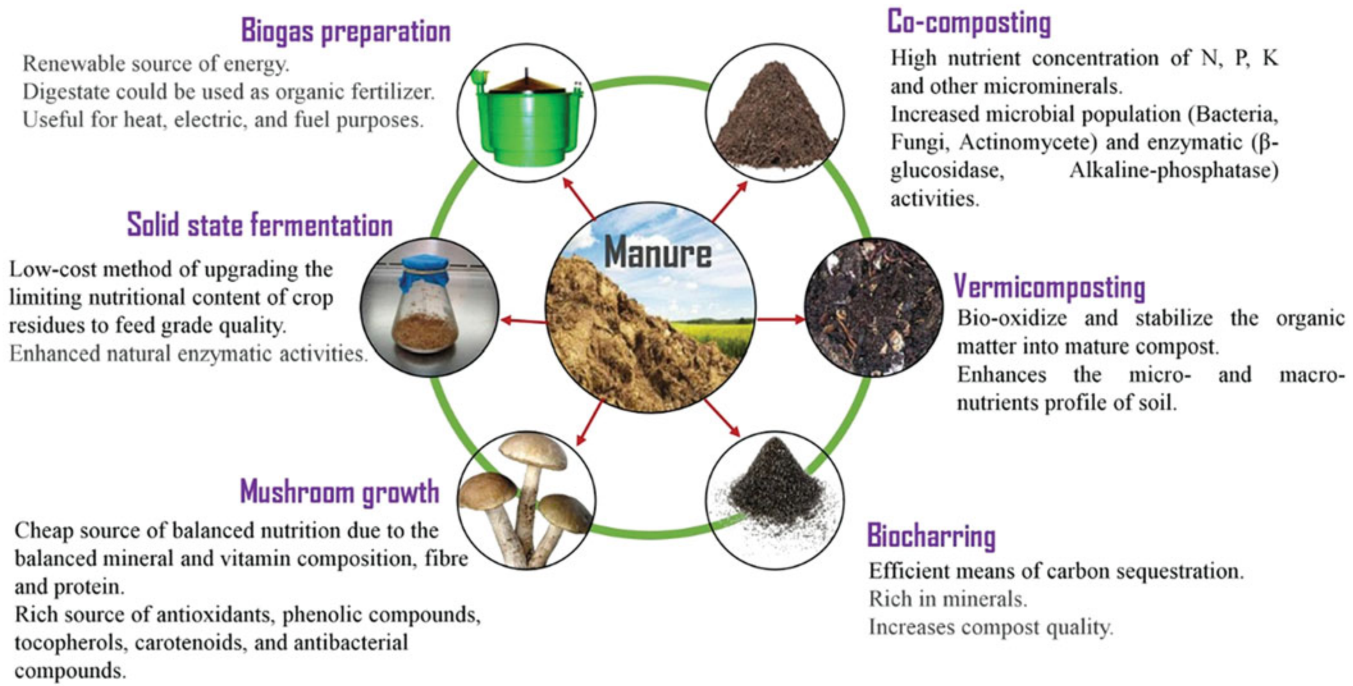

Fig. 1.4 Nutrient recycling from manure

coli has been reported for Niamey in Niger (Diogo et al. 2010). To reduce the problems, composting or vermicomposting could be used. Composting and vermicomposting are efficient processes for recycling manure because they bring stabilized and sanitized biodegraded end product for agriculture (Nasiru et al. 2014; Meena et al. 2020a). It can be used to convert substrate or waste from livestock or insect farming to organic fertilizer. Composting and vermicomposting processes represent a medium of making cheaper, locally, and readily available natural mineral through the decomposition of organic matter (Jangir et al. 2017, 2019; Kumar et al. 2020). Composting technique requires low investment in transforming fresh organic matter into fertilizer valuable organic matter by the microorganism. However, vermicomposting turns fresh organic matter into compost by joint activity of earthworms and microorganisms, which help in bio-oxidizing and stabilizing the organic matter into mature compost, thereby enhancing the micro- and macronutrients profile of soil (Nasiru et al. 2014; Mushtaq et al. 2019). The earthworm works by modifying the decomposing organic matter during their passage through the earthworms in a gut-associated process (Dominguez and Edwards 2011). These processes reduce N losses when fresh manure is applied, reduce odor, eliminate or reduce pathogens spreading and reduce the volume and weight of biomass (Peigne and Girardin 2004; Gomez-Brandon et al. 2008; Hristov et al. 2011).

1.5.1.1 Use of Human Feces Through Composting and Vermicomposting

Human feces are richly embedded with N and P because they consume crop and animal products. Efficient use of human feces could improve nutrient circulation in crop productivity. Yearly, about 3 of 3–5 Tg P that humans excrete spreads to the water bodies through the sewage system (Van Vuuren et al. 2010). Vermicomposting and composting represent good ways to recover nutrients from human feces and turn them to manure. Breakdown of organic matter during composting is due to the enzymes that hydrolyze complex macromolecules present in the decomposing materials (Delgado et al. 2004). Vermicomposting processes and composting process have a different effect on the nutrient profile of compost. Moya et al. (2019) showed vermicomposting of human feces resulted in higher nutrient availability than human feces composted. The composting process can save up to 42% of N, which varies with the type of procedures involved (Gomez-Brandon et al. 2008). Total N was 23 and 11 g kg^{-1} in compost and vermicompost prepared from human feces, respectively. Available N (ammonium and nitrate) in the feces vermicompost was 346% higher, i.e., 1009 vs. 217 mg kg^{-1}, organic carbon (g kg^{-1}) was 125% lower, i.e., 175 vs. 393 g kg^{-1}, P availability was ten times higher than in composted feces. In contrast, available potassium (K) of composted human feces was five times higher than vermicompost prepared from human feces. The CN (carbon/nitrogen) ratio of the compost and vermicompost feces was 17 and 16, respectively. This suggests that composting of human feces represents an excellent carbon (C) sequestration method compared to vermicomposting. Nevertheless, vermicomposting is a right method of increasing the N availability, thus decreasing its loss and environmental pollution. The P increase may be attributed to the digestion process of worms, which transformed the P from an organically bound to a soluble and available form. Other minor elements like zinc (Zn), magnesium (Mg), manganese (Mn), and Ca available in compost and vermicompost range from 3.5–349 and 0.9–946 mg kg^{-1}, respectively. This shows that they can be used as an alternative to mineral fertilizer. Inclusion of vermicompost and compost at 20% and 40% levels, maintained NUE at levels delivered by 40% inorganic fertilizer inclusion. Lesser quantity of vermicompost was needed to produce a similar efficiency to inorganic fertilizer.

1.5.1.2 Vermicomposting of Agricultural Waste

Vermicomposting processes help to stabilize and promote mineralization of organic matter and could be used as a soil health promoter or organic fertilizer. Earthworm (*Eisenia fetida*) is widely known for its ability to make compost out of agricultural wastes and animal manures (Edwards et al. 1998). Vermicomposting of cow dung and biogas plant waste having 70% moisture content increased cation exchange capacity (CEC) and mineral content (Ca, K, and P) by 25–104%. It increased N by 237–382% and decreased total C by 22–35% resulting in 80.9–83.9% decrease in CN ratio, which is below 15. The increase in the amount of P may be attributed to the conversion of P from organic matter into available form by enzymes present in earthworm gut such as acid phosphatases and alkaline phosphatases (Le Bayon and Binet 2006). Sharma and Garg (2017) reported that compost produced from sheep (*Ovis aries*), cow (*Bos taurus*), buffalo (*Bubalus bubalis*), and goat (*Capra aegagrus hircus*) manure with earthworm had higher N, P, and K values, produced odor free and homogenous vermicompost, while the CN ratio ranged from 15 to 38%. High biomass gains of earthworm were observed under buffalo manure, which indicates the richness of nutrients in the manure. As such, vermicomposting could improve the fertilizer value of ruminant manure such as cattle, buffalo, etc., in a country like India, where it is reared extensively in the dairy industry.

1.5.1.3 Enrichment of Manure through Co-Composting

Continuous use of manure as fertilizer represents a way to improve nutrient use in the agricultural system. To encourage manure use, there is a need to upgrade the nutrient profile of manure to the fertilizer equivalence of inorganic fertilizer. The poultry industry is the fastest meat-producing industry in the livestock sector. Presently, there are over 22 billion poultry population globally (FAOSTAT 2017), the highest for any livestock. This represents a tremendous amount of nutrient concentration of N, P, K, and other microminerals (Christensen and Sommer 2013). The manure is nutrient-rich because broiler diet is nutrient-dense due to short fattening days. Compost made from co-composting of 70% poultry waste, 30% rice husk, and 2% rock phosphate was found to have improved the CEC and decreased CN ratio of composted manure (10.8) compared to unenriched compost (24.83) (Mushtaq et al. 2019). Application of about 100 kg-N ha^{-1} of such compost improved growth and nutritional value of okra (*Abelmoschus esculentus*). The rock phosphate bio-oxidate the C into carbon dioxide (CO_2) thereby reducing the CN ratio. Similarly, co-composting of poultry or cattle manure alongside organic waste with non-reactive ground phosphate rock at 8:2 ratio increased organic P availability in the poultry manure compost than cattle manure compost. Furthermore, microbial population (bacteria, fungi, actinomycete) and enzymatic (β-glucosidase, alkaline phosphatase) activity in cattle manure compost were significantly ($p < 0.05$) higher than poultry manure compost (Kutu et al. 2019). This shows that P content and the fertilizer value of manure could be improved by co-composting with phosphate rock.

Fecal and crop waste recycling involves collecting crop–livestock waste and reducing their volume by composting. The organic matter from pineapple (*Ananas comosus*) leaves, and chicken slurry is rich in C, N, P, K, Ca, Mg, sodium (Na), Zn, copper (Cu), iron (Fe), and Mn in a range of 13.4–127,600 mg l^{-1} (Ch'ng et al. 2013). Co-composting of pineapple leaves with chicken slurry increased CEC by 108%, N by 40%, and P by 59%; whereas, C content was reduced throughout the co-composting resulting in decreased CN ratio (Ch'ng et al. 2013). The combined role of bacteria and fungi decomposed available cellulose, hemicellulose, lignin, and some resistant material. Also, the combination of heat, switching from mesophilic to thermophilic and microbial increase aid the breakdown of recalcitrant substances and set loose the polymers and linkages holding the nutrient and minerals. This compost can be used in vegetable and fruit production or garden plantation in urban and peri-urban areas, and to encourage back-yard farming.

1.5.2 Soil Amendment with Abattoir and Slaughterhouse Waste

In slaughterhouses, blood and rumen digesta are waste that is human inedible, and they contain part of the nutrient flow in agriculture. Despite nutrient content in blood, the use of blood to feed livestock is not encouraged due to zoonotic diseases. However, because the nutrient load is high, applying them to the soil could be a way to recover the nutrient. In a study, 2:1 and 3:1 mixture of waste blood and rumen digesta applied at 5 g kg^{-1} soil increased concentrations of C, N, and P and soil microbial population higher than diammonium phosphate (Roy et al. 2013). Besides, they also reported an increased number of tomato (*Lycopersicon esculentum*) fruit and weight by 90–110, and 113–130% respectively, whereas chili (*Capsicum frutescens*) fruit number by 39–100% and fruit weight by 129–258%. Furthermore, sensory evaluation such as sourness, sweetness, and hotness of the grown chili and tomato was identical to usual tomato and chili. This method could be used to improve soil value in back-yard farming or to cultivate this crop.

1.5.3 Biochar

Biochar is an organic material produced by subjecting biomass such as agricultural and agroindustry waste products and animal wastes to pyrolysis in heat between 300 and 700 °C with limited oxygen (Lehmann 2009; Bajiya et al. 2017). Biochar represents a means of concentrating nutrients in large biomass into a char form. Pyrolyzing animal waste and crop residues instead of disposing-off could result in nutrient recovery and recycling (Adegbeye et al. 2020). During pyrolysis, carboxyl and phenolic groups are decomposed, and properties like surface area, porosity, labile, or recalcitrance of chemical elements are altered. Biochar can be made from several sources such as husks, manures, crop shells, and sawmill residue (Speratti et al. 2018; Mirheidari et al. 2019). Biochar nutrients could be less volatile, stable, and compact, which give room for its use as organic fertilizer. Biochar represents a means of C sequestration in agriculture through which agriculture can be eco-friendly. Therefore, it could improve soil C storage better than those directly from animal manure, crop wastes, and composts (Fig. 1.5) (Kimetu and Lehmann 2010).

1.5.3.1 Biochar from Animal Manure

Biochar could be included as additives in feed to improve livestock productivity. Mirheidari et al. (2019) reported that adding biochar prepared from walnut shell and chicken manure at the rate of 1 and 1.5% of the diet, respectively, improved milk yield, milk composition and fiber digestibility. The increasing demand for pork and other animal products could increase animal density, potentially resulting in an unprecedented increase in ammonia (NH_3) and nitrous oxide (N_2O) emissions coming from swine houses and litter if swine production continues in its business as usual manner (Adegbeye et al. 2019). Co-composting of animal manure rich in N could reduce its losses and increase nitrogen use efficiency. Compost made from a mixture of pig manure and biochar–microbial inoculant powder [made from rice straw and $>1 \times 10^8$ CFU (colony-forming units) g^{-1} facultative microbes (consisting *Lactobacillus*, *Flavobacterium*, *Candida*, *Bacillus*, and *Actinomadura*, etc.)] for 42 days increased the compost pH by 3.10%, decreased TKN, CN ratio, and cumulative NH_3 emissions, degraded organic matter, and detoxified the compost (Tu et al. 2019). The decrease in NH_3 is because biochar is efficient at its adsorption during the composting process (Steiner et al. 2010). Therefore, co-composting with biochar and microbial inoculants will help improve compost quality, and reduce NH_3 and N_2O released during composting.

1.5.3.2 Biochar from Crop Waste

Subsistence and medium-scale farmers are affected by limits in their access to inorganic P fertilizers (FAO 2005; Bationo et al. 2006). This results in an inability to fill the crop yield's potential, leading to increased yield gaps and food crop imports. Biochar of some crop–livestock waste could improve the reuse of minerals. The relatively small pool of native soil P causes phosphorous deficiency in soils globally (Vance et al. 2003). Using manure alone result in low to a suboptimal level of soil P (Kutu 2012). In an era challenged with P pollution and depletion in phosphate rocks, biochar could be an alternative source of organic P, resulting in decreased use of inorganic P.

Biochar from sawdust, corn cob, rice husk, coffee (*Coffea* spp.) husk, and groundnut (*Arachis hypogaea*) husk had 10.61, 10.68, 12.26, 15.83, and 20.50 mg kg^{-1} available P, respectively. Similarly, N and K range from 4.17–11.34 g kg^{-1} and 2.16–5.43 c mol kg^{-1}, respectively (Billa et al. 2019).

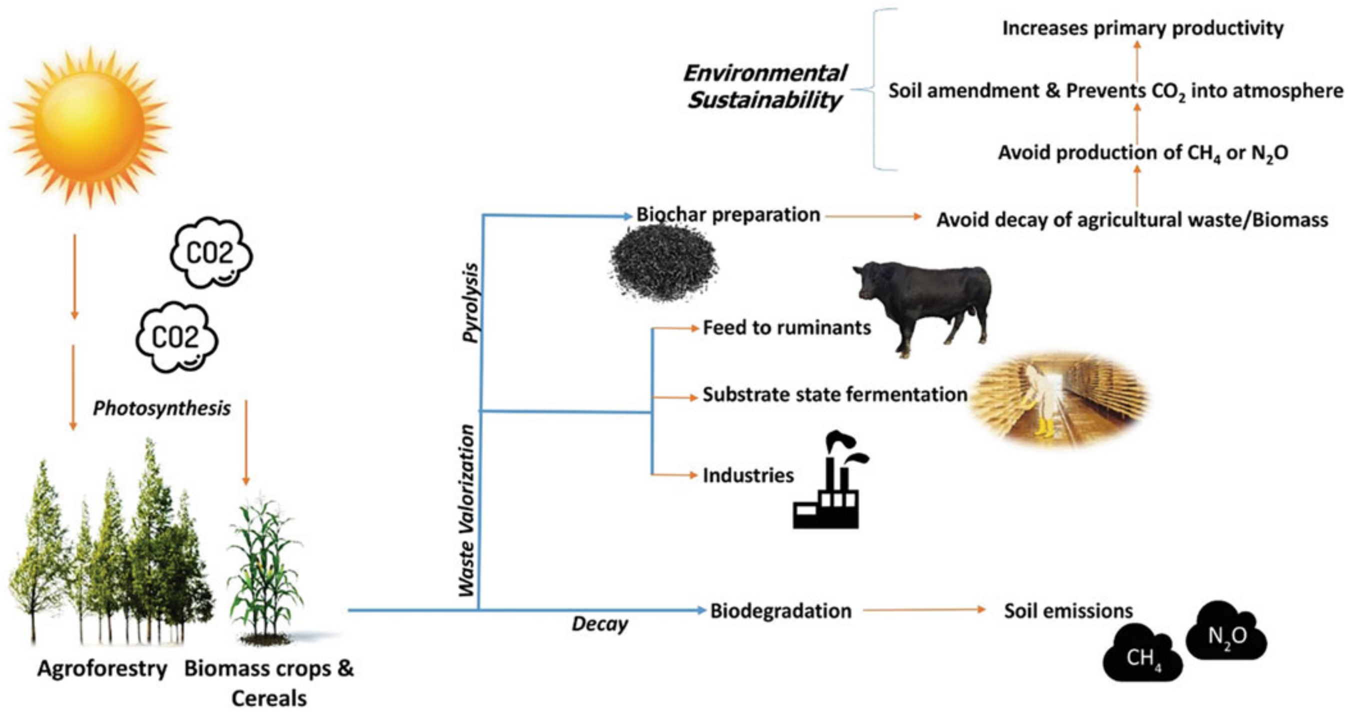

Fig. 1.5 Biochar use in agricultural production (Adapted Adegbeye et al. 2020)

Surprisingly, sawdust had low available P despite containing higher P (86 mg kg^{-1}) in its raw form (Adamu et al. 2014). This could be because wood-based biochar minerals tend to be more recalcitrant (Wang et al. 2016). Presently in Nigeria, sawdust is burnt because it has no commercial use, yet it is being produced in large quantities in sawmills. Biochar could serve as a source of recovering some nutrients in the sawdust. Biochar of poultry manure at 350–450 °C had 14.9–19.5 g kg^{-1} dry matter P and 10–14.8 labile P g kg^{-1} feedstock, respectively, and the N and K contents of poultry manure biochar increased (Keskinen et al. 2019). This could constitute a significant source of both macro and micronutrients for crop production. Alternatively, such biochar could be used as a source of organic P in livestock. Pyrolyzing at a lower temperature may increase mineral availability, which could be used as a supplement in livestock farming. A study found a higher N and P in biochar made from poultry litter at 350 °C compared to 700 °C (UC Davis Biochar Database 2019). This variation is because incomplete pyrolysis occurs at a lower temperature and this results in a higher mineral element in labile forms. The complete pyrolysis of biochar occurring at high temperature leads to the recalcitrance of the mineral element. This suggests that pyrolyzing at a lower temperature could increase the available P and other minerals. The use of labile biochar has been able to improve soil microbial activity (Ameloot et al. 2013). This increase could be due to better soil structure, moisture, and enhanced nutrient availability, which can be linked with NUE. Therefore, the biochar could be applied in livestock feeding as a partial substitute for inorganic P source.

1.5.3.3 Biochar on Plant Performance

Biochar has beneficial effects on crop and animal production systems and even reduced CH_4 emission in ruminants (Leng et al. 2012: Thuy Hang et al. 2019). Further, it has improved soil microbial community structure, soil enzyme activities, soil respiration, and C mineralization (Palansooriya et al. 2019). Also, its augmented soil pH increases microbial population and community structure (Kolton et al. 2016), soil moisture content, water retention capacity, water use efficiency, and, ultimately, crop yield (Fischer et al. 2019). Biochar applied at the rate of 1%, or 16 t ha^{-1} (tonne per hectare) equivalent was able to improve crop productivity and soil nutrient status (Speratti et al. 2018). Similarly, biochar of rice husk and straw compost (straw husk ash, sawdust, water hyacinth, and prebiotic decomposers) improved the rice straw's growth, i.e., plant height and the number of tillers with higher yields (Nisa et al. 2019). Furthermore, *Tibouchina* biochar elevated soil mineral concentration (Mg, K, Ca, and Zn), decreased soil acidity, increased soil microbiome species richness, and improved cassava growth (von Gunten et al. 2019). Biochar improves soil structure, soil moisture content, while inorganic fertilizer adds value to a nutrient-deficient soil. Co-application of biochar and inorganic fertilizer could work in a synergistic relationship. A two-year study on an intensive rice–wheat cropping system showed that co-application of 25 t ha^{-1} biochar plus 270 kg urea ha^{-1} increased rice yield, N uptake, and NUE (Wang et al. 2019). Likewise, Brazil nut husk biochar (1 ton ha^{-1}) or biochar plus fertilizer improved seedling survival and growth of some tropical trees (Lefebvre et al. 2019). Thus, biochar could be valuable in returning nutrients to the agronomic and agroforestry system.

1.6 Fungi as a Source for Improving the Resource Use Efficiency of Crop Residue

Fungi represent a vital source of improving the supply of nutrients through the use of fermentation technology from available alternative feed resources. Several fungi such as *Phlebia brevispora*, *P. fascicularia*, *P. floridensis*, and *P. radiata* (Sharma and Arora 2011), *Aspergillus terreus* (Jahromi et al. 2011), *Pleurotus florida* and *Pleurotus eous* (Sivagurunathan and Sivasankari 2015), and *Pleurotus pulmonarius (*Ariff et al. 2019) have produced valuable materials or improved the nutritional quality, digestibility and decreased the lignin content of crop residues. Therefore, fungi could play a crucial role in enhancing the output derivable from crop wastes.

1.6.1 Fungi on Crop Residue Quality

Fungi grow on plant materials rich in cellulose and lignin because they can synthesize multiple enzymes such as ferulic acid, cellulase, lignases, amylase, glucoamylase, esterases, and peptidases. These enzymes have fiber degrading properties capable of effectively biodegrading feed materials. Solid-state fermentation of crop residues with filamentous fungi represents a low-cost method of upgrading the limiting nutritional content to feed grade quality by taking advantage of natural enzymatic secretions. In practice, exogenous enzymes from *Aspergillus* spp. and *Trichoderma* spp. improve feed digestibility, yet, they could be expensive and inaccessible to farmers in many countries. Fungal inoculation and fermentation could enhance the protein content and digestibility of low-quality crop residue. Fermenting cassava residue for 7, 14, and 21 days with fungi *Aspergillus oryzae* increased the protein content by 104, 140, and 246.6%, respectively (Hong and Ca 2013). The crude protein also increased as the fermentation days increased. This affords farmers the choice of increasing the protein content of crop residue as desired. Likewise, fermentation with *A. oryzae* FK-923 and *A. awamori* F-524 decreased acid detergent fiber, neutral detergent fiber, phenol, and lignin, and improved the amino acid microbial protein. Also, the enzyme activity such as cellulase, xylanase, amylase, glucoamylase, laccase, and phytase increased during digestion (Fadel and El-Ghonemy 2015). Further, the enhanced enzymatic activities broke down cell linkages, and the phytase increased the availability of P. The increase phytase activity will release available P that is chelated with phytic acid thereby preventing P pollution (Konietzny and Greiner 2002).

Lignin remains a significant deterrent to effective digestibility of crop residues. It limits the impacts of gut microbes and their enzymatic activity/secretion on the lignocellulolytic materials. Many crop residues are lignocellulosic at harvest time, which reduces ruminants' ability to derive nutrients efficiently. Corn straw inoculated with *Pleurotus ostreatus* increased crude protein, soluble protein, and carbohydrate and decreased neutral detergent fiber. In vivo trial increased average daily gain and decreased feed conversion ratio by 31.05 and 13.35%, respectively, in Pelibuey lamb (Ramírez-Bribiesca et al. 2010).

White-rot fungus (*Phanerochaete chrysosporium*) produces a strong ligninolytic enzyme with energetic oxidative efficiency (Liang et al. 2010) and can efficiently degrade lignin into CO_2 (Hofrichter 2002). The use of 0.007% di-rhamnolipid biosurfactant alongside white-rot fungus decreased lignin content in rice straw by 54%. The degradation was as a result of the establishment of terrace-like fragments separated from the inner cellular fibers and the release of simple compounds (Liang et al. 2010). The biosurfactant improves the spread of water into rice straw pores, enhancing mass oxygen transfer into large areas (Van der Meer et al. 1992: Fu et al. 2007). Therefore, as oxygen level increases, there is a production of hydrogen peroxide and this induces lignocellulolytic activity (Sanchez 2009).

1.6.2 Fungi on Greenhouse Gases Mitigation

There is a positive correction between high fibrous diet, and GHGs production. Therefore, there is a need to develop and implement feeding and management strategies that reduce GHGs and subsequently increase feed digestibility (Faniyi et al. 2019). Several herbs like neem (*Azadirachta indica*), garlic (*Allium sativum)*, moringa (*Moringa oleifera)*, weeping willow (*Salix babylonica*) and exogenous enzyme have been used as additives in either or both *in vitro* and *in vivo* studies to reduce CH_4 production. Despite the relationship between high fibrous diet and CH_4 emission, fungi fermentation of fibrous materials could play a central role in improving digestibility and mitigating CH_4 emission. For example, fermentation with *A. terreus* can produce anti-methanogenic metabolites known as Lovastatin (Jahromi et al. 2013).

Mohd Azlan et al. (2018) reported that rice straw fermented with *A. terreus* for 14 days decreased methanogens due to the lovastatin, decreased fiber fraction and improved the dry matter digestibility. *Aspergillus terreus* fermentation offers farmers the ability to produce an animal protein with a less environmental footprint, increase degradability of crop residues and the manure obtained can be used for making vermicomposting or biochar for further nutrients recovery. Also, brown rot (*Serpula lacrymans*) produced reducing sugar when used for fermenting cacao pod, rice straw, corn cobs and leaves, and sugarcane (*Saccharum officinarum*) bagasse (Nurika et al. 2019). This indicates multiple substrate metabolism, tolerance to phenol, and ability to break up lignin structures.

1.6.3 Edible Fungi (Mushroom)

Fungi improve the nutrient content and digestibility of human-inedible plant biomass. The growing edible mushroom provides farmers with the option of meeting human nutritional needs from human inedible. Edible mushrooms are an option to reduce waste and generate valuable materials in agriculture. Mushroom farming is an efficient way of converting low-quality organic materials to quality food with higher nutritional and economic value. Mushroom is a cheap source of balanced nutrition due to the stable mineral and vitamin composition, fiber and protein. The amino acid profile is better than potatoes and carrots (*Daucus carota*) (Mattila et al. 2002). Furthermore, it contains antioxidants, phenol, and antibacterial compounds that can enhance the immune system and reduce stress (Borchers et al. 2008; Zhou et al. 2010). Mushrooms market represents a multi-billion-dollar industry, and its consumption has increased by a minimum of 3.7 kg per capital post-millennium (Royse et al. 2017). The substrate left after mushroom harvest can be anaerobically digested for bioenergy, fed to livestock, or burnt for ash. Farmers can use different substrates such as palm oil bunch and sawdust, etc., to grow mushroom.

1.6.3.1 Mushroom Growth/Fortification with Animal Waste/By-Product

Improving the biological efficiency and quality of the mushroom depends largely on the nutritional balance of the substrate (Rizki and Tamai 2011). Edible mushrooms can be grown on human-inedible organic resources. Furthermore, edible fungi's nutritional value can be improved in the growth phase by biofortification with organic minerals. Biofortification of white-rot fungi and *Lentinus squarrosulus* has grown on either coconut husk or palm kernel fiber and fortified with Ca-rich animal waste (eggshell of chicken, snail shell, and the bone shaft of the cow) or Ca salts produced Ca-enriched mushroom with adequate K, protein, and dietary fibers with low fat (Ogidi et al. 2019). The calcium compounds in the organic substrate influenced the growth and development of mushroom by stimulating the hyphal apices (Royse and Sanchez-Vazquez 2003). Similarly, chicken manure alongside paddy straw increased (*Pleurotus florida* and *Pleurotus eous*) growth by 100–105 g 500 g^{-1}, biological efficiency by 20–21%, and the nutritional content (carbohydrate and protein) of mushroom (Sivagurunathan and Sivasankari 2015). This shows that chicken manure can be a source of N in mushroom farming. However, the pathogenic load must be reduced.

1.6.3.2 Mushroom Waste and Spent Substrates

Spent mushroom substrates could be used as livestock feed because they have high cellulose and smaller particles. The delignification caused by ligninolytic enzymes like crude laccase and manganese peroxidase is also advantageous (Ariff et al. 2019). One percent oyster mushroom added as a substitute for maize in broiler diet increased final body weight, feed intake and had humoral immunity similar to the control (Fard et al. 2014). About 1–2 tons of the highly degradable spent mushroom substrate are produced from every 1 ton of mushroom harvested (Vijay 2005). These spent substrates are rich in C and other nutrients, and the multi-enzyme mushroom residue makes them rapidly digestible. They could be used as materials during anaerobic digestion for rural energy needs. The co-digestion of cattle dung with 2% spent mushroom waste increased biogas production up to 30% (Malik et al. 2014). This increment in gas production might be due to the activities of dehydrogenase, which increased by 12.8%. Likewise, the enzyme residue naturally present in mushroom may have enhanced the degradation of organic matter in cow dung, giving access to more surface area for an anaerobic microbial breakdown.

1.7 Waste and Their Use in Livestock Feeding

Increasing NUE from existing feed resources or tapping new non-conventional feed resources represents a way to bridge the gap between the demand and supply of feedstuff (Wadhwa and Bakshi 2016). Agroindustry and agri-food processing wastes, kitchen and restaurant waste are common resources available in crop–livestock–industrial–human interactions. Agricultural waste streams are not to be considered nutrient debiting/loss, rather valuable resources (Grimm and Wösten 2018). Therefore, diverting food waste into feed can replace the cereal-based diet of livestock with human-inedible resources (NAS 2019). The use of these inedible human waste and human-edible-but-wasted products as livestock feed may be an efficient way to recycle nutrient to produce high-value consumable livestock products. However, using the kitchen, agronomic and agri-food wastes alone in monogastric diet represents a threat to protein and micronutrient security. Feeding livestock with only human-inedible feedstuffs will reduce global livestock meat from poultry and swine by 53 and 91%, respectively, and egg production by 90% (Schader et al. 2015).

1.7.1 Cassava and Fruit Waste

Inedible human materials constitute over 80% of global livestock feed (Mottet et al. 2017). Despite environmental issues, ruminant farming permits incorporation of human-inedible wastes into livestock diet without adverse effect on global beef and milk production. Cassava (*Manihot esculentus*) is widely grown in the tropics and is a source of different product such as starch, fuel, and flour products. In cassava processing industries, there are bioethanol cassava wastes—a lignocellulolytic material containing some dissolved solids (mainly starch and minerals) are available at low cost. The nutrient in it shows that it has the potentials to be used in livestock feed as a substitute to established materials. Partial replacement of a conventional protein source Holstein-Friesian calves' ration with yeast (*Saccharomyces cerevisiae*) fermented cassava bioethanol wastes at the rate of 5–20% did not negatively affect nutrient intake, nutrient digestibility, rumen fermentation characteristic (rumen pH, rumen microbes, and total volatile fatty acids) (Cherdthong and Supapong 2019). Similarly, fermented cassava bioethanol waste added to duck diet at the rate of 5% improved the average daily gain and reduced the feed conversion ratio (Lei et al. 2019). Therefore, incorporating fermented cassava bioethanol into livestock diet may reduce environmental pollution from cassava industry and improve values derivable from cassava.

Pineapple fruit residue can be a treasured local resource alternative or a complement to green fodder as livestock feed. Adding 62% ensiled pineapple fruit residue to cattle diet improved the final body weight, digestibility, increased total average milk yield and milk fat, and decreased feed cost per kg gain by 24.19% compared to maize green fodder silage (Gowda et al. 2015).

1.7.2 Antinutritional Factor/Plant Metabolite Removal

Tannins could have both positive and negative impact on livestock. Tannins could be an antinutritional factor and it could be a phytochemical additive that manipulates the rumen ecosystem, mitigates CH_4 emission, and reduces fecal egg count, etc. Many non-conventional feed ingredients that are rich in protein have limited use because of secondary plant metabolites. Therefore, there is a need for processes that will reduce the antinutritional metabolites. The treatment of wheat straw with tannase reduced tannin content by 49.7–91.1% and further fermentation of wheat straw with white-rot fungi (*Ganoderma* spp.) plus 0.1% tannase increased crude protein, acid detergent fiber, and lignin degradation by 28, 17, and 57%, respectively (Raghuwanshi et al. 2014). The acid detergent fiber (ADF) and lignin degradation may be attributed to the increase in laccase and xylanase enzymatic activity during fermentation. Therefore, pretreatment of tannin-rich unconventional ingredient with *Penicillium charlesii*—a tannase producing enzyme—could be used to decrease tannin. Further fermentation with well-established fungus species such as *Aspergillus* spp., *Pleurotus* spp., and *Trichoderma* spp., etc., could improve the crude protein and decrease the fiber fraction components. Such fermentation process could help to improve the use of ingredients within the "unconventional" categories.

1.7.3 Kitchen and Dairy Waste

Kitchen, restaurant, and party wastes are valuable feedstuff for animal nutrition. They are available at little to no cost depending on the location of acquisition. They consist of bones, pepper, and other food ingredients which qualify them as "a junk of nutrients." However, before use, there is a need to improve the nutritional quality and microbial safety of these wastes. Probiotics can be used to advance food processing and quality, and amino acid utilization by lowering protein degradation (Mikulec et al. 1999). Application of *Lactobacilli* group (*L. acidophilus*, *L. casei*, *L. plantarum*, and *L. reuteri*) in fermenting restaurant waste increased the gross energy (1.55–8.1%), crude protein (3.39–11.97%), as well as increased dry matter content of restaurant waste (Saray et al. 2014). The proliferation of *Lactobacilli* using the carbohydrate and N compound in the trash as a source of protein could have increased the microbial protein resulting in an increased crude protein of the material. Besides, *Lactobacilli* can produce metabolites such as bacteriocin hydrogen peroxide, lactacins, and reuterin (b-hydroxy-propionaldehyde) (Avall-Jaaskelainen and Palva 2005; Parvez et al. 2006; Takahashi 2013). These compounds have vast antimicrobial activity against pathogenic microbes and could inhibit the growth of competing microorganisms, leaving available free N for microbial growth. This processed restaurant waste could be fed to pigs and poultry.

Dairy production is one of the most valuable agricultural products sector that resource-poor farmers can participate without much capital. Milk is a readily available animal protein source to smallholder farmers that are into ruminant farming. During processing, milk liquid (whey) is produced due to the coagulation of total solids in milk, and it is eliminated in both formal and informal cheese-making industry. However, in Nigeria's informal market, whey is sold together with the raw cheese "wàrà." Whey is rich in proteins, mineral elements (Ca, P, and sulfur), vitamins, and sugars, including lactose). Therefore, the use of whey in livestock diet is a means of recovering P, protein, and other minerals. Application of dried whey powder as replacements for soybean at the rate of 25–100% in lamb's diet improved total body weight gain by 17.65–56.87% and decreased feed conversion ratio (Kareem et al. 2018). Therefore, whey could be added as protein alternatives in fish, poultry, pig, and ruminant diet. It could be used to wet swine feed or mixed with fish feed before pelleting.

1.8 Nitrogen and Phosphorus Recovery and Release

A system that allows increased output compared to input and at the same time provides an opportunity for the reuse of the output within the producing system increases nutrient use efficiency (Rufino et al. 2006). The amount of N and P lost in crop and livestock production systems indicate poor NUE in the agricultural production systems (Adegbeye et al. 2020). An oversupply of nutrients especially overfeeding in intensive systems, or imbalance between nutrients (Sutton et al. 2013) causes these. Nitrogen utilization efficiency in livestock is low and it is usually in the range of 5–45% depending on animal species, system, and management (Oenema 2006), while the rest are passed out in feces and urine. Over 80% of N and 25–75% of P used, if not stored in the soil, gets lost to the environment (Sutton et al. 2013), indicating low NUE in agricultural systems. To improve the NUE in agrarian operations, there is a need for precise application of minerals tailored towards crop and animal needs, and recovery and recycling of nutrients from livestock manure and human feces.

If human excreta were collected over the globe, it would consist about one-third of the current N, P, and K consumption (Ellen MacArthur Foundation 2013). Human urine consists of 13% C, 14–18% N, 3.7% P, and 3.7% K, whereas the feces consist of >50% C, 5–7% N, 3–5.4% P, and 1–2.5% K (Vassilev et al. 2010; Rose et al. 2015). Furthermore, about 3 Tg P out of 3–5 Tg P in human excreta annually seeps into the river through sewage leaks (Van Vuuren et al. 2010). It is also projected that N (6.4 Tg) and P (1.6 Tg) emission at the beginning of the millennium would have increased by 87.5–150 and 85–139.5%, respectively, in 2050 (Van Drecht et al. 2009). This will be due to increased human population and improved economic state of developing countries of Africa, Asia, and the Middle East, resulting in a transition from cereals-based diets to animal protein, fruit, and vegetables rich diets. This necessitates the need to turn human excreta to organic fertilizer and recover some nutrients from it. In many countries of Africa under energy deficit, the recovery of nutrient from human excreta and manure could be a source of energy and biofertilizer. Similarly, biochar of human feces could be a means of recovering N, P, and other micro-elements (Adegbeye et al. 2020). It will help to reduce the quantity of any nutrient that could be lost and increase the value derivable from organic resources. This biochar of human excreta should be incompletely pyrolyzed to enhance available N, P, and K to ensure maximum nutrient recovery before its use as a soil conditioner.

1.8.1 Phosphorus Use: Recovery and Release

Direct application of urine or manure slurries to soil decreases N-fixing ability of soil (Di et al. 2002) and it causes overapplication of P than is needed by crop (Burns and Moody 2002). Furthermore, the nonrenewable of rock phosphate, and the possibility of P shortage in the future call for the need to get P from another source, which might include the recovery from wastewater and manure. To reduce P pollution, precipitation of struvite could be a medium of recovering P from animal manure (Burns and Moody 2002).

Struvite is a mineral substance that contains an equimolar amount of Mg, ammonium, and phosphate ions, and is measured as a good P source (Barak and Stafford 2006). Precipitation of struvite occurs during supersaturation—where over three ions in wastewater exceed struvite solubility (0.2 g l^{-1}) (Barak and Stafford 2006) or at a pH between 8.5 and 9.5 (Uysal et al. 2010). A 1 to 0.5 ratio of cow urine to brine (inexpensive source of Mg) produced the best struvite, and the struvite was added at up to 2 g kg^{-1} of soil, it resulted in optimal growth of green gram (*Vigna radiata*) (Prabhu and Mutnuri 2014). If up to 40 g struvite is produced per liter of urine, up to 12,176 t of struvite could be produced in a day. This has the potential to be used as a good source of phosphate fertilizer. Similarly, application of nitric acid to dairy cattle slurry allows the recovery of P content in 2.5 h and anaerobic digesta in 48 hours by 100 and 90%, respectively, and further precipitation with Mg:N:P in ratio 1:1:1 at pH 8.0 resulted in the formation of—amorous Ca-phosphates—a potential fertilizer (Oliveira et al. 2016).

The use of phytase—a hydrolytic enzyme—to initiate the dephosphorylation of phytate (Abdel-Megeed and Tahir 2015) or decreasing the phytic acid in feed ingredient could be an effective way to reduce inorganic P excretion and accumulation on livestock farms. Therefore, as phytic acid decreases, an increase in phytase indicates improved availability of imbedded or inherent organic P. Wheat straw fermented with fungal *Aspergillus ficuum* at 30 °C increased phytase production by 22-folds and decreased phytic acid by 57.4% after 144 h of incubation (Shahryari et al. 2018). Thus, fermenting wheat straw or crop residues abundant in phytate before feeding them to livestock could increase the availability of organic P and decrease P excretion to the environment.

1.8.2 Controlled Release of Nitrogen

Controlled release of urea with the barrier to decrease its dissolution rate represents a way to minimize N losses from the field (Shavit et al. 2003). Low cost, nontoxic, and biodegradable suitable coating barrier could improve nutrient efficiency and, reduce the environmental risks (Tomaszewska et al. 2002). Application of bio-polymeric materials, such as lignin from waste lignin controlling N released from urea. The waste lignin modified by acetylation reaction—acetylated kraft lignin and sulfite lignin slowed the release of N by enhancing its hydrophobicity (Behin and Sadeghi 2016). This delayed water permeability and mineral release. Furthermore, the dissolution rate of urea decreased by 25–45% as coating material increased from 5 to 15%. This could be applied in coating other mineral compounds to control its release in livestock. For example, coated urea in the ruminant feed caused the controlled release of N in the rumen, thereby decreasing the N_2O emission and total GHGs emission potentiality (Reddy et al. 2019a, b).

1.9 Microlivestock Farming

Bushmeat (meat from animals in the wild) from a giant rat, antelope, cane rat, deer, monkey, and snails have always served as an alternative source of animal protein among rural dwellers. This contradicts the public opinion that rural dwellers lack animal protein. However, recent endemic diseases such as Ebola, Lassa fever, and Monkeypox in Nigeria were linked with consumption of bushmeat. As alternatives, domestication of some microlivestock in developing countries can serve as a means of improving protein security. Examples of microlivestock that could be reared are snails, grasscutter, and rabbit, etc. Rearing these animals requires fewer resources such as land, water, and feed. Sales of unprocessed or processed bushmeat empower women because it provides financial leverage and security. Meat from microlivestock such as grasscutter, snail, and rabbit commands premium price than beef, chevon, mutton, milk, and egg in Nigeria, etc. Therefore, rearing these animals could improve the use of land as agricultural resources (Fig. 1.6).

1.9.1 Snail Farming

Snail farming is also known as heliculture. The meat of snail is high in protein, Fe, Ca, Mg, and low in fat. Breeds of snail such as *Archachatina marginata* and *Achatina achatina* can be reared and fed with fruit waste and leaves, as well as other household and food processing by-product. However, they must not contain salt. Snails can be fed with concentrate, pawpaw (*Asimina triloba*) fruit, eggplant (*Solanum melongena*), banana (*Musa* spp.), plantain (*Plantago major*), tomatoes, cucumber (*Cucumis sativus*), palm fruits, maize chaff—a by-product of *ogi* extract, and potato peel, etc. This provides a means of improving the use of space on the farms by producing a high-quality protein that could be sold at a premium price, both

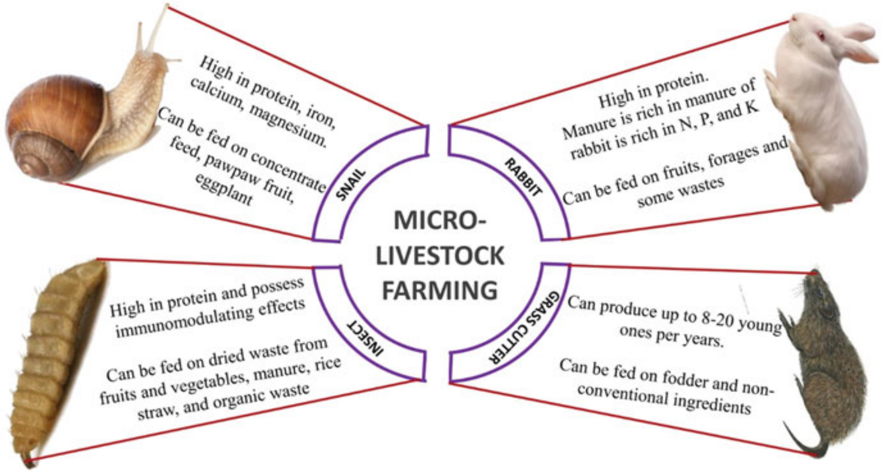

Fig. 1.6 Microlivestock farming

in Nigeria and West African regions. Their hermaphrodite nature permits them to reproduce quickly, laying up to 400 hatchable eggs. Setting up a snail farm is cheap; it could be raised in vehicle tire, drum, pots, old tanks, baskets, and cages.

1.9.2 Rabbits Farming

Domestication of rabbits is well documented. Rabbit production empowers women and children (El-Adawy et al. 2019). It offers smallholder farmer who cannot afford large livestock the chance to produce animal protein, as well as provide a source of fertilizer. The gestation period of a rabbit is short about 31 days and they are a highly prolific animal that can produce up to 5–10 bunnies per kindling. Rabbit can be fed fruits, forages, and some wastes that are not stale. Anecdotal observation indicates that it tastes better than chicken. Besides, the manure of rabbit is rich in N, P, and K so that it could be used as fertilizer. The N, P, and K in rabbit feces are 140, 75, and 53% higher than chicken manure, respectively (Lebas et al. 1996). Furthermore, Tabaro et al. (2012) reported that rabbit farming could be integrated with aquaculture reared in an earthen pond and the pond fertilized with rabbit feces produced higher fish mass and fish-net production.

1.9.3 Grasscutter

Grasscutter (*Thryonomys swinderianus)* farming is highly profitable. The grasscutter reproduces quickly and in good numbers. Grasscutter has a gestation period of 140–150 days and can produce up to 8–20 young ones/years, and an adult, it can reach up to 3–6 kg. They are herbivores, as such; they can be maintained on cheap materials such as elephant grass (*Pennisetum purpureum*), guinea grass (*Megathyrsus maximus*), sugarcane, gamba grass (*Andropogon gayanus*), root and pitch of oil and coconut palm, pawpaw, groundnut, cassava, etc. Financially, grasscutter commands a premium price in a big restaurant. Other non-conventional ingredients can be used to formulate the diet of grasscutter. Edoror and Okoruwa (2017) fed grasscutter with cocoa bean (*Theobroma cacao*) shell and cocoyam (*Colocasia esculenta*) peel as a replacement for grass, i.e., CS30 (30% cocoa beans shell + 40% cocoyam peel and 30% concentrate diet) and CS40 (40% cocoa bean shell + 30% cocoyam peel and 30% concentrate diet). The CS30 and CS40 had final bodyweight that is 6 and 24.81% higher than control diet and lower feed conversion ratio.

1.10 Phytotherapy

Phytotherapy is the application of the phytochemical's existent in the plant for health benefits in animals. Phytotherapy provides a means of improving the health and growth performance of livestock among farmers that cannot afford drugs and veterinary services. Furthermore, the use of phytogenic feed additives to improve growth performance and feed digestibility also plays a part in RUE. For resource-poor farmers, the use of herbs from local plant serves as alternatives to expensive and inaccessible commercial anthelmintic. These plants may be referred to as nutraceuticals based on health benefit derived from them rather than a direct contribution to animal nutrition (Waller and Thamsborg 2004). Frequent applications and improper dosage result in the ineffectiveness of acaricidal and antihelminth. Furthermore, the interest of consumers to go "green" in most of their consumables has drawn attention to the agelong but abandoned practices of using herbs for animal's health benefit. This practice known as ethnoveterinary medicine draws inspiration from traditional practices where the range of plant(s) or plant extract suitable for treating almost every parasitic disease of livestock is used (International Institute of Rural Reconstruction 1994). Diseases that phytochemicals seek to address are both internal and external parasites such as helminths, mange, ringworms, mastitis, foot rot, etc. (Table 1.1).

Several plants from both agronomic, botanical and agroforestry system in the form of herbs, seeds, root, and barks have been used in treating livestock. Neem and pawpaw seed were able to decrease the population of parasitic egg in poultry chicken (Feroza et al. 2017). In Nigeria, Usman (2016) reported that nomadic farmers use herbs, stems, seeds, leaf extract to control diarrhea, fever, ringworm, mastitis, mange, poor milk let down, foot and mouth disease through topical, oral, or feeding to animals. In small ruminants, intestinal worms such as *Haemonchus contortus*, *Strongyloides* spp., and *Trichostrongylus* spp. are prevalent parasites, and herbs can control them. Ameen et al. (2010) reported that both aqueous extract and the dry seed of pawpaw decreased *Haemonchus contortus*, *Trichostrongylus* spp., *Strongyloides* spp., and *Ostertagia* spp. population in West African Dwarf sheep. Adebayo et al. (2019) report that 10% inclusion of scent leaf (*Ocimum gratissimum)* in the diet

Table 1.1 Summary of plants influence on pathogens

Pathogen	Animal species	Plant parts	Form	Quantity	Effects	Reference
Not specified	Zebu cattle (*Bos taurus indicus*)	Neem leaf and Ata leaf (*Annona reticulata*)	Powder	200 mg kg^{-1}	84–95% decrease in fecal egg count in 28 days	Sarker (2014)
Haemonchus contortus	Sheep	Neem, Tobacco (*Nicotiana* spp.), *Calotropis procera* flower, and *Trachyspermum ammi* seed	Aqueous herbal formulations	2 g and 4 g kg^{-1} body weight	Decreased fecal egg count by 91.6 and 96.2% after 15 days	Zaman et al. (2012)
Mixed nematode (*Haemonchus contortus*, *Trichostrongylus* spp., *Oesophagostomum columbianum*, and *Trichuris ovis*)	Sheep	*Trianthema portulacastrum* whole plant and leaves of *Musa paradiasiaca*	Crude aqueous methanolic extract	8 g kg^{-1}	Decreased the fecal egg by 85.6 and 80.7%, respectively, on 15 days post-partum	Hussain et al. (2011)
Gastrointestinal nematode	Goats	Neem, pineapple, bitter gourd (*Momordica charantia*), and clove (*Syzygium aromaticum*)	Ethanol extract	100 mg kg^{-1}	73–83% decrease against gastrointestinal nematodes in goats within 9 days	Sujon et al. (2008)
Eimeria spp., *Trichostrongylus* spp., and *Strongyloides* spp.	Grazing goat	Neem seed extract and garlic extract	Extract mixed with feed bock	1.5–3 and 2%, respectively	Decreased Eimeria spp., by 51–93%, *Trichostrongylus* spp. by 3.8–35%, and *Strongyloides* spp. by 54–73% in 60 days	Sales et al. (2016)
Rhipicephalus (*Boophilus*) *microplus*	In vitro	A methanol extract of pawpaw seeds		100 mg ml^{-1}	Killed over 80% of their larvae and over 90% adults in 15 days, inhibited egg mass per replicate	Shyma et al. (2014)

reduced fecal worm egg count in west African dwarf goat. The reduction in the counts of goat fed scent leaf diets could be attributed to the presence of antinutritional factors especially tannin and phenols—which can control some endoparasites in animals (Butter et al. 2001).

Grazing animals and those in an extensive system of ruminant production are mainly affected by worm and other parasitic infestation. To control this parasitic infection requires regular treatment with anthelmintic. Applying herbs in block licks could help reduce the population of these endoparasites. In application, herbal extracts with anthelmintic potential could be added during mineral and salt lick production as a means to control internal parasites (Sales et al. 2016).

Ticks are economically significant parasites in the tropics and subtropics and are prevalent in wet seasons (Bram 1983). Besides their potential to cause anemia, their sites of binding could cause injury to animals and be a source of secondary infections. However, prolonged use and overuse of chemical ectoparasites resulted in the large-scale development of resistance in these parasites (Adenubi et al. 2016). Extract of pawpaw seeds inhibits egg mass per replicate and oviposition, prevents the reproduction of tick (*Rhipicephalus* (*Boophilus*) *microplus*) and killed over 80% of larvae (Shyma et al. 2014). This shows that topical application of such extract could be used to control tick both in the rainy and dry season in tropical regions where nomadic farming is still in practice.

1.11 Conclusions

The sustainable practices in agriculture of today will be essential for food security. To ensure food security in developing countries of the world, smallholder farmer must be given feasible options that would help them in providing nutrient from their soil and ensure that nutrient in the agricultural system continues to flow in circular manure through the coupling of crop and livestock system even if they are spatially apart. In the agricultural industry, nutrient recovery and recycling remain the feasible option than is economical, eco-friendly, easily adoptable, and multi-beneficial to farmers and livestock feeding. Insect farming, anaerobic digestion, wastewater reuse, composting, vermicomposting, biochar, fungal intervention, and microlivestock farming are options that could aid the reuse and even add values to waste generated in the agricultural system. Tremendous cooperation will play an imperative role in developing the recovery of phosphate from urine and also the development of portable or fixed biogas chamber for anaerobic digestion. These options will ensure that smallholder farmers can increase the efficiency of essential agricultural resources—land, water, and nutrients.

1.12 Future Perspectives

Resources distribution/availability towards agriculture will continue to shrink as other industries compete for the same agriculture related bio-resources for agriculture and livestock feeding. This chapter provides insight into the enormous benefits that could be derived from recycling waste. Wastes in agriculture may not be a “bad” thing but rather, an opportunity to convert organic materials to other forms. We reckon that through the transformation of wastes or linkage of wastes from one agricultural system to the other, nothing will be termed as waste. Smallholder/resource-constrained farmers will find great potential in collaborating on the use of by-products as rich resources. Large-/medium-scale farmers can turn waste to economically valuable resources through biochar, water recycling, composting, mushroom production, and nutrient recovery. Due to the scarcity of water resources in regions, agriculture-industry wastewater can be redistributed after applying minimal treatment to convert it into valuable irrigation resources in the future. Similar, human and animal wastes could be a source of fertilizer and raw materials for mining nitrogen and phosphorus. The nitrogen and phosphorus obtained from it may not be as the common inorganic fertilizer as we know it today, but if these minerals are mined from both human and animal feces, they could reduce environmental pollution. Besides, vermicomposting and composting processes can serve as an alternative to inorganic fertilizer or can work in synergy with inorganic fertilizer thereby reducing the quantity of inorganic fertilizer used. Furthermore, microlivestock is of great potential as it will bring “the wild” nearer to consumers and help to reduce encroachment into the wild thereby reducing the dangerous wildlife are exposed to in the hand of a poacher. Similarly, due to the controlled condition of rearing it will reduce the chance of zoonotic diseases. Finally, microbes especially fungi have an enormous role in ensuring resource use efficiency. The roles range from enhancing rumen degradation, food production in mushroom, greenhouse gas mitigation, increasing the nutritional value of food by decreasing common antinutritional factors in plants. Increasing the reuse or recycling of agricultural system wastes through redistribution, recovery, value addition, etc., will improve nutrient use efficiency. However, nothing is a waste in agriculture.

References

Abdel-Megeed A, Tahir A (2015) Reduction of phosphorus pollution from broiler waste through supplementation of wheat-based broiler fed with phytase. J Chem 2015:1–3

Abdulkadir A, Leffelaar PA, Agbenin JO, Giller KE (2013) Nutrient flows and balances in urban and peri-urban agroecosystems of Kano, Nigeria. Nutr Cycl Agroecosyst 95:231–254

Abudi ZN, Hu Z, Abood AR, Liu D, Gao A (2019) Effects of alkali pre-treatment, total solid content, substrate to inoculum ratio, and pH on biogas production from anaerobic digestion of mango leaves. Waste Biomass Valor. https://doi.org/10.1007/s12649-018-0437-0

Adamu UK, Almu H, Adam IA, Sani SA (2014) Evaluation of nutrient composition of some cereals and legumes crops residues as compost materials. Bayero J Pure Appl Sci 7:52–54

Adebayo KO, Aderinboye RY, Sanwo KA, Oyewusi IK, Isah OA (2019) Growth performance and fecal worm egg count of West African dwarf goats fed diets containing varying levels of *Ocimum gratissimum* (Scent leaf). Livest Res Rural Dev 31:1–8

Adegbeye MJ, Elghandour MM, Monroy JC, Abegunde TO, Salem AZM, Barbabosa-Pliego A, Faniyi TO (2019) Potential influence of Yucca extract as feed additive on greenhouse gases emission for a cleaner livestock and aquaculture farming – a review. J Clean Prod 239:118074

Adegbeye MJ, Ravi Kanth Reddy P, Obaisi AI, Elghandour MMY, Oyebamiji KJ, Salem AZM, Morakinyo-Fasipe O, Cipriano-Salazar M, Camacho-Díaz LM (2020) Sustainable agriculture options for production, greenhouse gasses and pollution alleviation, and nutrient recycling in emerging and transitional nations - an overview. J Clean Prod 242:118319

Adenubi OT, Fasina FO, McGaw LJ, Eloff JN, Naidoo V (2016) Plant extracts to control ticks of veterinary and medical importance: a review. South Afr J Bot 105:178–193

Ameen SA, Adedeji OS, Ojedapo LO, Salihu T, Fabusuyi CO (2010) Anthelmintic potency of pawpaw (*Carica papaya*) seeds in West African Dwarf (WAD) sheep. Glob Vet 5:30–34

Ameloot N, De Neve S, Jegajeevagan K, Yildiz G, Buchan D, Funkuin YN, Prins W, Bouckaert L, Sleutel S (2013) Short-term CO_2 and N_2O emissions and microbial properties of biochar amended sandy loam soils. Soil Biol Biochem 57:401–410

Ariff IF, Bahrin EK, Ramli N, Abd-Aziz S (2019) Direct use of spent mushroom substrate from *Pleurotus pulmonarius* as a readily delignified feedstock for cellulase production. Waste Biomass Valor 10:839–850

Avall-Jaaskelainen S, Palva A (2005) Lactobacillus surface layers and their applications. FEMS Microbiol Rev 29:511–529

Azagoh C, Ducept F, Garcia R, Rakotozafy L, Cuvelier M-E, Keller S, Lewandowski R, Mezdour S (2016) Extraction and physicochemical characterization of *Tenebrio molitor* proteins. Food Res Int 88:24–31

Azlan PM, Jahromi MF, Ariff MO, Ebrahimi M, Candyrine SCL, Liang JB (2018) *Aspergillus terreus* treated rice straw suppresses methane production and enhances feed digestibility in goats. Trop Anim Health Prod 50:565–571

Bajiya R, Lakhran H, Kumar S, Seema A (2017) Biochar for enhancing agricultural sustainability under climate change. Int J Curr Microb Appl Sci 6(2):1876–1883

Barak P, Stafford A (2006) Struvite: a recovered and recycled phosphorus fertilizer. In: Proceedings of the Wisconsin fertilizer, aglime and pest management conference, vol 45

Barragán-Fonseca K, Pineda-Mejia J, Dicke M, Van Loon JJA (2018) Performance of the black soldier fly (Diptera: Stratiomyidae) on vegetable residue-based diets formulated based on protein and carbohydrate contents. J Econ Entomol 111:2676–2683

Bationo A, Hartemink A, Lungu O, Okoth P, Smaling E, Thiombiano L (2006) African soils: their productivity and profitability of fertilizer use. In: Proceedings of the African fertilizer summit, Abuja, Nigeria, 9–13 June 2006

Behin J, Sadeghi N (2016) Utilization of waste lignin to prepare controlled-slow release urea. Int J Recycl Org Waste Agric 5:289–299

Biasato I, Gasco L, De Marco M, Rotolo L, Dabbo S, Capucchio MT, Biasibettia E, Tarantola M, Bianchi C, Cavallarin L, Gai F, Pozzo L, Dezzuttof D, Bergagna S, Schiavone A (2017) Effects of yellow mealworm larvae (Tenebrio molitor) inclusion in diets for female broiler chickens: implications for animal health and gut histology. Anim Feed Sci Technol 234:253–263

Billa SF, Angwafo TE, Ngome AF (2019) Agro-environmental characterization of biochar issued from crop wastes in the humid forest zone of Cameroon. Int J Recycl Org Waste Agric 8:1–13. https://doi.org/10.1007/s40093-018-0223-9

Bloukounon-Goubalan AY, Saïdou A, Chrysostome AM, Kenis M, Amadji GL, Igué AM, Mensah GA (2019) Physical and chemical properties of the agro-processing by-products decomposed by larvae of *Musca domestica* and *Hermetia illucens*. Waste Biomass Valor, pp 1–9. https://doi.org/10.1007/s12649-019-00587-z

Blümmel M, Haileslassie A, Herrero M, Beveridge M, Phillips M, Havlik P (2015) Feed resources vis-à-vis livestock and fish productivity in a changing climate. In: Malik PK (ed) Livestock production and climate change. CAB International, Wallingford, pp 8–24

Borchers AT, Krishnamurthy A, Keen CL, Meyers FJ, Gershwin ME (2008) The immunobiology of mushrooms. Exp Biol Med 233:259–276

Bram A (1983) Tick-borne livestock diseases and their vectors: the global problem. In: Ticks and tick-borne diseases, FAO Animal Production and Health. Food and Agriculture Organization, Rome, pp 7–11

Burns RT, Moody LB (2002) Phosphorus recovery from animal manures using optimized struvite precipitation. In: Proceedings of coagulants and flocculants: global market and technical opportunities for water treatment chemicals. Chicago, Illinois

Burton CH, Turner C (2003) Manure management. Treatment strategies for sustainable agriculture. In: Proceedings of the MATRESA, EU accompanying measure project, 2nd edn. Silsoe Research Institute, Bedford

Butter NL, Dawson JM, Wakelin D, Buttery PJ (2001) Effect of dietary condensed tannins on gastrointestinal nematodes. J Agric Sci 137:461–469

Cai M, Zhang K, Zhong W, Liu N, Wu X, Li W, Zheng L, Yu Z, Zhang J (2019) Bioconversion-composting of golden needle mushroom (*Flammulina velutipes*) root waste by black soldier fly (*Hermetia illucens*, Diptera: Stratiomyidae) larvae, to obtain added-value biomass and fertilizer. Waste Biomass Valor 10:265–273

Cappellozza S, Leonardi MG, Savoldelli S, Terova G, Moretto E, Badaile A, Concheri G, Saviane A, Bruno D, Bonelli M, Caccia S, Casartelli M, Tettamanti G (2019) A first attempt to produce proteins from insects by means of a circular economy. Animals 9:278

Cardoso DB, Liberal Véras RM, de Carvalho FF, Magalhães AL, Vasconcelos G, Maciel M, Madruga MS, Urbano SA, Silva J (2019) Physicochemical parameters, fatty acid profile, and sensory attributes of meat from lambs fed with cassava dregs in replacement of corn. Trop Anim Health Prod 51:1515–1521. https://doi.org/10.1007/s11250-019-01840-2

CAWMA (2007) Water for food, water for life: a comprehensive assessment of water management in agriculture Comprehensive Assessment of Water Management in Agriculture. International Water Management Institute, London, pp 1–45

Ch'ng HY, Ahmed OH, Kassim S, Majid N (2013) Co-composting of pineapple leaves and chicken manure slurry. Int J Recycl Org Waste Agric 2:23

Cherdthong A, Supapong C (2019) Improving the nutritive value of cassava bioethanol waste using fermented yeast as a partial replacement of protein source in dairy calf ration. Trop Anim Health Prod 51:2139–2144. https://doi.org/10.1007/s11250-019-01911-4

Christensen ML, Sommer SG (2013) Manure characterization and inorganic chemistry. In: Sommer SG, Christensen ML, Schmidt T, Jensen LS (eds) Animal manure: recycling. Treatment and Management. Wiley, London, pp 41–66

Collavo A, Glew RH, Huang YS, Chuang LT, Bosse R, Paoletti MG (2005) In: Collavo A (Ed.), House cricket small scale farming. Science Publishers, Enfield

Dabbou S, Gai F, Biasato I, Capucchio MT, Biasibetti E, Dezzutto D, Meneguz M, Plachà I, Gasco L, Schiavone A (2018) Black soldier fly defatted meal as a dietary protein source for broiler chickens: effects on growth performance, blood traits, gut morphology and histological features. J Anim Sci Biotechnol 9:49. https://doi.org/10.1186/s40104-018-0266-9

Delgado A, Solera del Río R, Sales D (2004) Study of the co-composting process of municipal solid waste and sewage sludge: stability and maturing. In: Bernal M, Moral R, Clemente R, Paredes C (eds) Proceedings of the 11th conference of the FAO on recycling of agricultural municipal and industrial residues in agriculture. Ramiran, Murcia, pp 257–260

Di HJ, Cameron KC, Silva RG, Russell JM, Barnett JW (2002) A lysimeter study of the fate of 15-N labelled nitrogen in cow urine with or without farm dairy effluent in a grazed dairy pasture soil under flood irrigation. N Z J Agric Res 45:235–244

Diogo RVC, Buerkert A, Schlecht E (2010) Horizontal nutrient fluxes and food safety in urban and peri-urban vegetable and millet cultivation of Niamey, Niger. Nutr Cycl Agroecosyst 87:81–102

Dobermann D, Field LM, Michaelson LV (2019) Using *Hermetia illucens* to process Ugandan waragi waste. J Clean Prod 211:303–308

Dominguez J, Edwards CA (2011) Relationships between composting and vermicomposting. In: Edwards CA, Arancon NQ, Sherman R (eds) Vermiculture technology earthworms, organic wastes, and environmental management. CRC Press, Boca Raton, pp 11–26

Edoror OM, Okoruwa MI (2017) Growth performance of grasscutter (*Thryonomys swinderianus*) fed graded levels of cocoa bean shell with cocoyam peel as a replacement for forage grass. Livest Res Rural Dev *29:1–8*

Edwards CA, Dominguez J, Neuhauser EF (1998) Growth and reproduction of *Parionyx excavates* (Perr.) (Megascolecidae) as factors in organic waste management. Biol Fertil Soils 27:155–161

El-Adawy MM, Aboelez ZR, Rashad AM, Elghandour M, Adegbeye MJ, Ashtoy M, Cipriano-Salazar M, Hernandez S, Salem AZM (2019) Effects of dietary inclusion of dried Kochia indica Wight tree foliages on growth performance and nutrient digestibility of growing rabbits. Agrofor Syst 93:352. https://doi.org/10.1007/s10457-019-00352-0

Ellen MacArthur Foundation (2013) Towards the circular economy: opportunities for the consumer goods sector. Ellen MacArthur Foundation, Cowes

Fadel M, El-Ghonemy DH (2015) Biological fungal treatment of olive cake for better utilization in ruminant nutrition in Egypt. Int J Recycl Org Waste Agric 4:261–271

Faniyi TO, Prates ER, Adegbeye MJ, Adewumi MK, Elghandour M, Salem AZM, Ritt LA, Zubieta AS, Stella L, Ticiani E, Jack A (2019) Prediction of biogas and pressure from rumen fermentation using plant extracts to enhance biodigestibility and mitigate biogases. Environ Sci Pollut Res 26:27043–27051. https://doi.org/10.1007/s11356-019-05585-1

FAO (2005) Fertilizer use by crop in South Africa. A publication by Food and Agriculture Organization of the United Nations (FAO), TC/D/Y5998E/1/5.05/300, 37

FAO (2011) The state of the world's land and water resources for food and agriculture (SOLAW) – managing systems at risk. Food and Agriculture Organization of the United Nations, Rome

FAO (2013) Food wastage footprint: impact on natural resources. Summary report. Food and Agriculture Organization of the United National, Rome

FAO (2019) Five practical actions towards low-carbon livestock. FAO, Rome, pp 1–40

FAOSTAT (2017). http://www.fao.org/faostat/en/#compare

Fard SH, Toghyani M, Tabeidian SA (2014) Effect of oyster mushroom wastes on performance, immune responses and intestinal morphology of broiler chickens. Int J Recycl Org Waste Agric 3:141–146

Feroza S, Arijo AG, Zahid IR (2017) Effect of papaya and neem seeds on *Ascaridia galli* infection in broiler chicken. Pak J Nematol 35:105–111

Fischer BMC, Manzoni S, Morillas L, Garcia M, Johnson MS, Lyon SW (2019) Improving agricultural water use efficiency with biochar a synthesis of biochar effects on water storage and fluxes across scales. Sci Total Environ 657:853–862

Fu HY, Zeng GM, Zhong H, Yuan XZ, Wang W, Huang GH, Li JB (2007) Effects of rhamnolipid on degradation of granular organic substrate from kitchen waste by a Pseudomonas aeruginosa strain. Colliods Surf B 58:91–97

Fuglie K, Wang SL (2012) Productivity growth in global agriculture. Popul Dev Rev 27:361–365

Gao Z, Wang W, Lu X, Zhu F, Liu W, Wang X, Lei C (2019) Bioconversion performance and life table of black soldier fly (*Hermetia illucens*) on fermented maize straw. J Clean Prod 230:974–980

Gomez-Brandon M, Lazcano C, Domınguez J (2008) The evaluation of stability and maturity during the composting of cattle manure. Chemosphere 70:436–444

Gowda S, Vallesha N, Awachat VB, Anandan S, Pal DT, Prasad CS (2015) Study on evaluation of silage from pineapple (*Ananas comosus*) fruit residue as livestock feed. Trop Anim Health Prod 47:557–561

Grimm D, Wösten HAB (2018) Mushroom cultivation in the circular economy. Appl Microbiol Biotechnol 102:7795–7803

Herrero M, Thornton PK, Notenbaert A, Msangi S, Wood S, Kruska RL, Dixon J, Bossio D, van de Steeg JA, Freeman HA, Li X, Rao P (2009) Drivers of change in crop-livestock systems and their potential impacts on agro-ecosystems services and human well-being to 2030. In: Study commissioned by the CGIAR system wide livestock programme (SLP). ILRI, Nairobi

Hofrichter M (2002) Review: lignin conversion by manganese per-oxidase (MnP). Enzym Microb Technol 30:454–466

Hong TTT, Ca LT (2013) The protein content of cassava residue, soybean waste and rice bran is increased through fermentation with *Aspergillus oryzae*. Livest Res Rural Dev *25:1–8*

Hristov AN, Hanigan M, Cole A, Todd R, McAllister TA, Ndegwa PM, Rotz A (2011) Review: ammonia emissions from dairy farms and beef feedlots. Can J Anim Sci 91:1–35

Hussain A, Khan MN, Iqbal Z, Sajid MS, Khan MK (2011) Anthelminthic activity of *Trianthema portulacastrum* L. and *Musa Paradisiaca* L, against gastrointestinal nematode of sheep. Vet Parasitol 179:92–99

Ilyas SZ (2006) A case study to bottle the biogas in cylinders as source of power for rural industries development in Pakistan. World Appl Sci J 1:127–130

International Institute of Rural Reconstruction (1994) Ethnoveterinary medicine in Asia: an information kit on traditional animal health care practices, 2nd edn. International Institute of Rural Reconstruction (IIRR), Silang

Jahromi MF, Liang JB, Rosfarizan M, Goh YM, Shokryazdan P, Ho YW (2011) Efficiency of rice straw lignocelluloses degradability by *Aspergillus terreus* ATCC 74135 in solid state fermentation. Afr J Biotechnol 10:4428–4435

Jahromi MF, Liang JB, Mohamad RM, Goh YM, Shokryazdan P, Ho YW (2013) Lovastatin-enriched rice straw enhances biomass quality and suppresses ruminal methanogenesis. Biomed Res Int 2013:1–13

Jangir CK, Panghaal D, Kumar S, Meena RS, Prince A (2017) Enriching soil carbon stock through mitigating soil erosion. In: Rao RK, Sharma PK, Raghuraman M, Singh JK (eds) Agricultural, allied sciences & biotechnology for sustainability of agriculture, nutrition & food security. Mahima Publications, Jaipur, pp 415–419

Jangir CK, Kumar S, Meena RS (2019) Significance of soil organic matter to soil quality and evaluation of sustainability. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Enfield, pp 357–381

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017a) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in Indo-Gangetic Plains of India. J Curr Microb Appl Sci 6(3):152–163

Kakraliya SK, Kumar N, Dahiya S, Kumar S, Yadav DD, Singh M (2017b) Effect of integrated nutrient management on growth dynamics and productivity trend of wheat (*Triticum aestivum* L.) under irrigated cropping system. J Plant Dev Sci 9(1):11–15

Kapdi SS, Vijay VK, Rajesh SK, Rajendra P (2006) Upgrading biogas for utilization as a vehicle fuel. J Energy Environ 7:387–393

Kareem AN, Rahman JA, Alnaemi A (2018) Effect of feeding dried whey on the efficiency of Iraqi Awassi lambs. J Res Ecol 6:1893–1898

Keskinen R, Hyväluoma J, Sohlo L, Help H, Rasa K (2019) Fertilizer and soil conditioner value of broiler manure biochars. Biochar 1:259–270. https://doi.org/10.1007/s42773-019-00020-7

Kimetu JM, Lehmann J (2010) Stability and stabilisation of biochar and green manure in soil with different organic carbon contents. Soil Res 48:577

Kolton M, Graber ER, Tsehansky L, Elad Y, Cytryn E (2016) Biochar-stimulated plant performance is strongly linked to microbial diversity and metabolic potential in the rhizosphere. New Phytol 213:1393–1404

Konietzny U, Greiner R (2002) Molecular and catalytic properties of phytate-degrading enzymes (phytases). Int J Food Sci Technol 37:791–812

Kumar S, Lakhran H, Meena RS, Jangir CK (2017) Current need of sustainable food and forage production to eliminate food and forage insecurity under current climatic era. Forage Res 44 (1):165–173

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, New York, pp 337–375. https://doi.org/10.1007/978-981-13-7264-3_10

Kutu FR (2012) Effect of conservation agriculture management practices on maize productivity and selected soil quality indices under South Africa dryland conditions. Afr J Agric Res 7 (3839):3846

Kutu FR, Mokase TJJ, Dada OA, Rhode HJ (2019) Assessing microbial population dynamics, enzyme activities and phosphorus availability indices during phospho-compost production. Int J Recycl Org Waste Agric 8:87–97

Lalander C, Diener S, Zurbrügg C, Vinnerås B (2019) Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*). J Clean Prod 208:211–219

Le Bayon RC, Binet F (2006) Earthworm changes the distribution and availability of phosphorus in organic substrates. Soil Biol Biochem 38:235–246

Lebas F, Coudert P, Rochambeau H, Thébault R (1996) Le lapin: elevage et pathologie (nouvelle version revisitée). Collection FAO Production et Santé animales, Rome

Lefebvre D, Roman-Danobeytia F, Soete J, Cabanillas F, Corvera R, Ascorra C, Fernandez LE, Silman M (2019) Biochar effects on two tropical tree species and its potential as a tool for reforestation. Forests 10:678

Lehmann J (2009) Terra preta nova where to from here? In: Woods WI, Teixeira WG, Lehmann J, Steiner C, WinklerPrins A (eds) Terra Preta Nova: a tribute to Wim Sombroek. Springer, Berlin, pp 473–486

Lei L, Feng Z, Li Q, Xue X, Zhang D, Liu Z, Liu Y, Ren Y, Zhao S (2019) Fermented cassava bioethanol waste as substitute of protein in diet for growth performance and carcass evaluation on meat ducks. Trop Anim Health Prod 51:1049–1056

Leng RA, Preston TR, Inthapanya S (2012) Biochar reduces enteric methane and improves growth and feed conversion in local “Yellow” cattle fed cassava root chips and fresh cassava foliage. Livest Res Rural Dev 24:1–8

Liang YS, Yuan XZ, Zeng GM, Hu CL, Zhong H, Huang DL, Tang L, Zhao JJ (2010) Biodelignification of rice straw by *Phanerochaete chrysosporium* in the presence of dirhamnolipid. Biodegradation 21:615–624

Liu Z, Minor M, Morel P, Najar-Rodriguez AJ (2018) Bioconversion of three organic wastes by black soldier fly (Diptera: Stratiomyidae) Larvae. Environ Entomol 47:1609–1617

Looy H, Dunkel FV, Wood JR (2013) How then shall we eat? Insect eating attitudes and sustainable foodways. Agric Hum Values 31:131–141

Lowder S, Skoet J, Raney T (2016) The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev 87:16–29

Makkar HPS, Tran G, Heuzé V, Ankers P (2014) State-of-the-art on use of insects as animal feed. Anim Feed Sci Technol 197:1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008

Malik K, Mehta SY, Anand RC (2014) Co-digestion of spent mushroom substrate with cattle dung for enhancement of biogas production. Haryana Agric Univ J Res 44:25–28

Manurung R, Supriatna A, Esyanthi RR, Putra RE (2016) Bioconversion of rice straw waste by black soldier fly larvae (*Hermetia illucens* L.): optimal feed rate for biomass production. J Entomol Zool Stud 4:1036–1041

Mattila P, Salo Väänänen P, Könkö K, Aro H, Jalava T (2002) Basic composition and amino acid contents of mushrooms cultivated in Finland. J Agric Food Chem 50:6419–6422

Meena RS, Kumar V, Yadav GS, Mitran T (2018) Response and interaction of Bradyrhizobium japonicum and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Kumar S, Bohra JS, Lal R, Yadav GS, Pandey A (2019) Response of alley cropping-grown sesame to lime and sulphur on yield and available nutrient status in an acidic soil of Eastern India. Energy Ecol Environ 4:65–74

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Mertenat A, Diener S, Zurbrügg C (2019) Black soldier fly biowaste treatment – assessment of global warming potential. Waste Manag 84:173–181

Mikulec Z, Serman V, Mas N, Lukac Z (1999) Effect of probiotic on production results of fattened chickens fed different quantities of protein. Vet Arch 69:199–209

Mirheidari A, Torbatinejad NM, Shakeri P, Mokhtarpou A (2019) Effects of walnut shell and chicken manure biochar on in vitro fermentation and in vivo nutrient digestibility and performance of dairy ewes. Trop Anim Health Prod 51:2153–2160. https://doi.org/10.1007/s11250-019-01909-y

Mohd-Noor S, Lim JW, Mah-Hussin MT, Ramli A, Chew T-L, Bashir MJK, Tan W-E, Beniers JJA (2016) Potential of protein and lipid productions from black soldier fly larvae fed with mixture of waste coconut endosperm and soybean curd residue. AIP Conf Proc 2016:020098. https://doi.org/10.1063/1.5055500

Mottet A, Henderson B, Opio C, Falcucci A, Tempio G, Silvestri S, Chesterman S, Gerber PJ (2017) Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Global Food Sec 14:1–8

Moya B, Parker A, Sakrabani R, Mesa B (2019) Evaluating the efficacy of fertilisers derived from human excreta in agriculture and their perception in Antananarivo, Madagascar. Waste Biomass Valor 10:941–952. https://doi.org/10.1007/s12649-017-0113-9

Mushtaq M, Iqbal MK, Khalid A, Khan RA (2019) Humification of poultry waste and rice husk using additives and its application. Int J Recycl Org Waste Agric 8:15–22

NAS (2019) National Academies of Sciences, Engineering, and Medicine, Science breakthroughs to advance food and agricultural research by 2030. The National Academies Press, Washington, DC, pp 1–243

Nasiru A, Ibrahim MH, Ismail N (2014) Nitrogen losses in ruminant manure management and use of cattle manure vermicast to improve forage quality. Int J Recycl Org Waste Agric 3:57. https://doi.org/10.1007/s40093-014-0057-z

Nasr M, Tawfik A, Suzuki M, Ookawara S (2015) Mathematical modeling of bio-hydrogen production from starch wastewater via up-flow anaerobic staged reactor. Desalin Water Treat 54:50–58

National Biogas Program (2008) EREDPC/SNV, Ethiopia. Training of trainers (TOT) on construction and supervision of SINIDU model biogas plant for Ethiopia. In: Trainee's manual. SNV - Netherlands Development Organisation, The Hague, pp 1–111

Nigussie A, Kuyper TW, de Neergaard A (2015) Agricultural waste utilization strategies and demand for urban-waste compost: evidence from smallholder farmers in Ethiopia. Waste Manag 44:82–93

Nisa K, Siringo-ringo L, Zaitun M (2019) The utilization of agricultural waste biochar and straw compost fertilizer on paddy plant growth. IOP Conf Ser Mater Sci Eng 506:1–14

Notenbaert A, Herrero M, Kruska R, You L, Wood S, Thornton P, Omolo A (2009) Classifying livestock production systems for targeting agricultural research and development in a rapidly changing world. Discussion Paper No. 19. ILRI (International Livestock Research Institute), Nairobi, Kenya. p 41

Nurika I, Suhartini S, Barker C (2019) Biotransformation of tropical lignocellulosic feedstock using the brown rot fungus *Serpula lacrymans*. Waste and Biomass Valor. https://doi.org/10.1007/s12649-019-00581-5

Nyakeri EM, Ayieko MA, Amimo FA, Salum H, Ogola HJO (2016) An optimal feeding strategy for black soldier fly larvae biomass production and faecal sludge reduction. J Insects Food Feed 1:1

Oenema O (2006) Nitrogen budgets and losses in livestock systems. Int Congr Ser 1293:262–271

Ogidi CO, Akindulureni ED, Agbetola OY, Akinyele BJ (2019) Calcium bioaccumulation by *Pleurotus ostreatus* and *Lentinus squarrosulus* cultivated on palm tree wastes supplemented with calcium-rich animal wastes or calcium salts. Waste Biomass Valor. https://doi.org/10.1007/s12649-019-00760-4

Oliveira V, Ottosen M, Labrincha J, Dias-Ferreira C (2016) Valorisation of phosphorus extracted from dairy cattle slurry and municipal solid wastes digestates as a fertilizer. Waste Biomass Valor 7:861–869

Olugbemide AD, Lajide L, Adebayo A, Owolabi BJ (2019) Enhanced biogas production from rice husk through solid-state chemical pretreatments. Waste Biomass Valor. https://doi.org/10.1007/s12649-018-00567-9

Palansooriya KN, Wong JT, Hashimoto Y, Huang L, Rinklebe J, Chang SX, Bolan N, Wang H, Ok YS (2019) Response of microbial communities to biochar-amended soils: a critical review. Biochar 1:3–22

Parvez S, Malik KA, Ah Kang S, Kim HY (2006) Probiotics and their fermented food products are beneficial for health. J Appl Microbiol 100:1171–1185

Peigne J, Girardin P (2004) Environmental impacts of farm-scale composting practices. Water Air Soil Pollut 153:45–68

Prabhu M, Mutnuri S (2014) Cow urine as a potential source for struvite production. Int J Recycl Org Waste Agric 3:49. https://doi.org/10.1007/s40093-014-0049-z

Raghuwanshi S, Misra S, Saxena RK (2014) Treatment of wheat straw using tannase and white-rot fungus to improve feed utilization by ruminants. J Anim Sci Biotechnol 5:13

Ramankutty N, Mehrabi Z, Waha K, Jarvis L, Kremen C, Herrero M, Rieseberg LH (2018) Trends in global agricultural land use: Implications for environmental health and food security. Annu Rev Plant Biol 69:1–14

Ramírez-Bribiesca JE, Soto-Sánchez A, Hernández-Calva LM, Salinas-Chavira J, Galaviz-Rodriguez J, Cruz-Monterrosa J, Vargas-López S (2010) Influence of *Pleurotus ostreatus* spent corn straw on performance and carcass characteristics of feedlot Pelibuey lambs. Indian J Anim Sci 80:754–757

Reddy PRK, Kumar DS, Rao ER, Seshiah CV, Sateesh K, Reddy YPK, Hyder I (2019a) Assessment of eco-sustainability vis-à-vis zoo-technical attributes of soybean meal (SBM) replacement with varying levels of coated urea in Nellore sheep (*Ovis aries*). PONE 14:e0220252. https://doi.org/10.1371/journal.pone.0220252

Reddy PRK, Kumar DS, Rao ER, Seshiah CV, Sateesh K, Rao KA, Reddy YPK, Hyder I (2019b) Environmental sustainability assessment of tropical dairy buffalo farming vis-a-vis sustainable feed replacement strategy. Sci Rep 9:16745. https://doi.org/10.1038/s41598-019-53378-w

Rizki M, Tamai Y (2011) Effects of different nitrogen rich substrates and their combination to the yield performance of oyster mushroom (*Pleurotus ostreatus*). World J Microbiol Biotechnol 27:1695–1702

Rockström J, Gordon L, Folke C, Falkenmark M, Engwall M (1999) Linkages among water vapor flows, food production, and terrestrial ecosystem services. Conserv Ecol 3:1–28

Rockstrom J, Williams J, Daily G, Noble A, Matthews N, Gordon L, Wetterstrand H, DeClerck F, Shah M, Steduto P, de Fraiture C, Hatibu N, Unver O, Bird J, Sibanda L, Smith J (2017) Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46:4–17

Roessler R, Mpouam SE, Muchemwa T, Schlecht E (2016) Emerging development pathways of urban livestock production in rapidly growing West Africa cities. Sustainability 8:1199. https://doi.org/10.3390/su8111199

Rose C, Parker A, Jefferson B, Cartmell E (2015) The characterization of feces and urine: a review of the literature to inform advanced treatment technology. Crit Rev Environ Sci Technol 45:1827–1879

Roy M, Karmakar S, Debsarcar A, Sen PK, Mukherjee J (2013) Application of rural slaughterhouse waste as an organic fertilizer for pot cultivation of solanaceous vegetables in India. Int J Recycl Org Waste Agric 2:6

Royse DJ, Sanchez-Vazquez JE (2003) Influence of precipitated calcium carbonate ($CaCO_3$) on shiitake (*Lentinula edodes*) yield and mushroom size. Bioresour Technol 90:225–228

Royse DJ, Baars J, Tan Q (2017) Current overview of mushroom production in the world. In: Zied DC, Pardo-Giminez A (eds) Edible and medicinal mushrooms: technology and applications. Wiley, Hoboken, pp 5–13

Rufino MC, Rowe EC, Delve RJ, Giller KE (2006) Nitrogen cycling efficiencies through resource-poor African crop–livestock systems. Agric Ecosyst Environ 112:261–282

Rufino MC, Hengsdijk H, Verhagen A (2009) Analysing integration and diversity in agro ecosystems by using indicators of network analysis. Nutr Cycl Agroecosyst 84:229–247

Sales A, Gomes MG, Alcantara MD, Cordao A, Oliveira LH (2016) Efficacy of garlic and neem seed extract as control over gastrointestinal parasites in goats grazing on rangeland. In: Proceedings of the 10th international rangeland congress. The future management of grazing and wild lands in a high-tech world, pp 1161–1162

Sanchez C (2009) Lignocellulosic residues: biodegradation and bioconversion by fungi. Biotechnol Adv 27:185–194

Saray SC, Hosseinkhani A, Janmohammadi H, Zare P, Daghighkia H (2014) Thermal and probiotic treatment effects on restaurant waste for incorporation into poultry diet. Int J Recycl Org Waste Agric 3:71. https://doi.org/10.1007/s40093-014-0071-1

Sarker AH (2014) Efficacy of Neem (*Azadirachta indica*) and Ata (*Annona Reticulata*) leaf as natural anthelmintics and their effects on milk production and body weight of zebu cattle under subsistence farming condition. Bangladesh Agricultural University, Mymensingh, MSc dissertation, pp 1–106

Schader C, Muller A, Scialabba J, Isensee A, Erb KH, Smith P, Makkar HP, Klocke P, Leiber F, Schwegler P, Stolze M, Niggli U (2015) Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. J R Soc Interf 12:20150891

Shah TA, Ullah R (2019) Pretreatment of wheat straw with ligninolytic fungi for increased biogas productivity. Int J Environ Sci Technol 16:7497–7508. https://doi.org/10.1007/s13762-019-02277-8

Shahryari Z, Fazaelipoor MH, Setoodeh P, Nair RB, Taherzadeh MJ, Ghasemi Y (2018) Utilization of wheat straw for fungal phytase production. Int J Recycl Org Waste Agric 7:345–355. https://doi.org/10.1007/s40093-018-0220-z

Sharma R, Arora DS (2011) Biodegradation of paddy straw obtained from different geographic locations by means of *Phlebia* spp. for animal feed. Biodegradation 22:143–152. https://doi.org/10.1007/s10532-010-9383-7

Sharma K, Garg VK (2017) Management of food and vegetable processing waste spiked with buffalo waste using earthworms (*Eisenia fetida*). Environ Sci Pollut Res 24:7829–7836

Shavit U, Reiss M, Shaviv A (2003) Wetting mechanisms of gel-based controlled-release fertilizers. J Control Release 88:71–78

Shyma KP, Gupta JP, Ghosh S, Patel KK, Singh V (2014) Acaricidal effect of herbal extracts against cattle tick Rhipicephalus (Boophilus) microplus using in vitro studies. Parasitol Res 113:1919–1926

Singh P, Wani SP, Pathak P, Sahrawat KL, Singh AK (2011) Increasing crop productivity and water use efficiency in rainfed agriculture. In: Integrated watershed management in rainfed agriculture. CRC Press, London, pp 315–347

Sivagurunathan P, Sivasankari S (2015) Influence of chicken manure on biological efficiency of Pleurotus spp. Waste Biomass Valor 6:23–28. https://doi.org/10.1007/s12649-014-9320-9

Souza Filho PF, Zamani A, Taherzadeh MJ (2019) Edible protein production by filamentous fungi using starch plant wastewater. Waste Biomass Valor 10:2487–2496

Speratti AB, Johnson MS, Sousa HM, Dalmagro HJ, Couto EG (2018) Biochars from local agricultural waste residues contribute to soil quality and plant growth in a Cerrado region (Brazil) Arenosol. GCB Bioenergy 10:272–286. https://doi.org/10.1111/gcbb.12489

Stangel PJ (1995) Nutrient cycling and its importance in sustaining crop–livestock systems in sub Saharan Africa: an overview. In: Powell JM, Rivera SF, Willams TO (eds) Proceedings of the international conference on livestock and sustainable nutrient cycling in mixed model farming system of sub-Saharan Africa, vol 1. International Livestock Centre for Africa, Addis Ababa, pp 37–57

Stark F, González-García E, Navegantes L, Miranda T, Poccard-Chapuis R, Archimède H, Moulin C (2018) Crop-livestock integration determines the agroecological performance of mixed farming systems in Latino-Caribbean farms. Agronom Sust Dev 38:4. https://doi.org/10.1007/s13593-017-0479-x

Steiner C, Das KC, Nathan M, Lakly D (2010) Reducing nitrogen loss during poultry litter composting using biochar. J Environ Qual 39:1236–1242

Sujon MA, Mostofa M, Jahan M, Das AR, Rob S (2008) Studies on medicinal plants against gastrointestinal nematodes of goats. Bangl J Vet Med 6:179–183

Supriyatna A, Manurung R, Esyanti RR, Putra RE (2016) Growth of black soldier larvae fed on cassava peel wastes, an agriculture waste. J Entomol Zool Stud 4:161–165

Sutton MAB, Howard CM, Bekunda M, Grizzetti B, de Vries W, van Grinsven HJM, Abrol YP, Adhya TK, Billen G, Davidson EA, Datta A, Diaz R, Erisman JW, Liu XJ, Oenema O, Palm C, Raghuram N, Reis S, Scholz RW, Sims T, Westhoek H, Zhang FS (2013) Our nutrient world: the challenge to produce more food and energy with less pollution. Centre for Ecology and Hydrology, Edinburgh, pp 1–128

Tabaro SR, Mutanga O, Rugege D, Micha J-C (2012) Rabbit droppings as an organic fertilizer in earthen ponds, to improve growth and production of Nile tilapia, *Oreochromis niloticus* L., in Rwanda. Rwanda J 28:11–38

Taimeh A (2013) Mitigation and adaptation options for rainfed agriculture in West Asia and North Africa. In: Sivakumar MV et al (eds) Climate change and food security 239 in West Asia and North Africa. FAO, Rome, pp 239–253. https://doi.org/10.1007/978-94-007-6751-513

Takahashi J (2013) Lactic acid bacteria and mitigation of GHG emission from ruminant livestock. Intech Open 19:451–466

Teenstra E, De Buisonje F, Ndambi A, Pelster D (2015) Manure management in the (Sub) tropics; training manual for extension workers. (University & Research Centre) Livestock Research, Livestock Research Report 919, Wageningen, Wageningen UR

Thornton PK (2010) Livestock production: recent trends, future prospects. Philos Trans R Soc B 365:2853–2867

Thornton PK, Rosenstock T, Förch W, Lamanna C, Bell P, Henderson B, Herrero M (2018) A qualitative evaluation of CSA options in mixed crop-livestock systems in developing countries. In: Lipper L et al (eds) Climate smart agriculture, natural resource management and policy 52. FAO, Rome, pp 385–423. https://doi.org/10.1007/978-3-319-61194-517

Thuy Hang L, Preston TR, Ba NX, Dung D (2019) Effect of biochar on growth and methane emissions of goats fed fresh cassava foliage. Livest Res Rural Dev 31:1–5

Tomaszewska M, Jarosiewicz A, Karakulski K (2002) Physical and chemical characteristics of polymer coatings in CRF formulation. Desalination 146:319–323

Tu Z, Ren X, Zhao J, Awasthi SK, Wang Q, Awasthi MK, Zhang Z, Li R (2019) Synergistic effects of biochar/microbial inoculation on the enhancement of pig manure composting. Biochar 1:127–137

UC Davis Biochar Database (2019). http://biochar.ucdavis.edu/download/. Accessed 2 November 2018

Usman IS (2016) Ethno-veterinary care amongst the nomadic Fulani herdsmen in southern zone of Adamawa State, Nigeria. J Anim Sci Vet Med 1:108–117

Uysal A, Yilmazel YD, Demirer GN (2010) The determination of fertilizer quality of the formed struvite from effluent of a sewage sludge anaerobic digester. J Hazard Mater 181:248–254

Van der Meer AB, Beenackers AACM, Burghard R, Mulder NH, Fok JJ (1992) Gas/liquid mass transfer in a four-phase stirred fermentor: effects of organic phase hold-up and surfactant concentration. Chem Eng Sci 47:2369–2374

Van Drecht G, Bouwman AF, Harrison J, Knoop JM (2009) Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. Glob Biogeochem Cycles 23:Gb0a03

Van Vuuren DP, Bouwman AF, Beusen AHW (2010) Phosphorus demand for the 1970-2100 period: a scenario analysis of resource depletion. Glob Environ Change Human Policy Dim 20:428–439

Vance CP, Uhde-Stone C, Allan D (2003) Phosphorus acquisition and use: critical adaptation by plants for securing non-renewable resources. New Physiol 15:423–447

Vanlauwe B, AbdelGadir AH, Adewopo J, Adjei-Nsiah S, Ampadu-Boakye T, Asare R, Baijukya F, Baars E, Bekunda M, Coyne D, Dianda M, Dontsop-Nguezet PM, Ebanyat P, Hauser S, Huising J, Jalloh A, Jassogne L, Kamai N, Kamara A, Kanampiu F, Kehbila A, Kintche K, Kreye C, Larbi A, Masso C, Matungulu P, Mohammed I, Nabahungu L, Nielsen F, Nziguheba G, Pypers P, Roobroeck D, Schut M, Taulya G, Thuita M, Uzokwe V, van Asten P, Wairegi L, Yemefack M, Mutsaers H (2017) Looking back and moving forward: 50 years of soil and soil fertility management research in sub-Saharan Africa. Int J Agric Sustain 15:613–631

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan Region, India. Int J Chem Stud 5(4):1558–1560

Vassilev SV, Baxter D, Andersen LK, Vassileva CG (2010) An overview of the chemical composition of biomass. Fuel 89:913–933

Velho VF, Mohedano RA, Filho PB, Costa RH (2012) The viability of treated piggery wastewater for reuse in agricultural irrigation. Int J Recycl Org Waste Agric 1:10

Vijay B (2005) Formulation for compost for white button mushroom. In: Rai RD, Upadhyay RC, Sharma SR (eds) Frontier in mushroom biotechnology. National Research Centre for Mushroom, Solan, pp 80–87

Vlyssides A, Mai S, Barampouti EM (2015) Energy generation potential in Greece from agricultural residues and livestock manure by anaerobic digestion technology. Waste Biomass Valor 6:747–757. https://doi.org/10.1007/s12649-015-9400-5

von Gunten K, Hubmann M, Ineichen R, Gao Y, Kurt KO, Alessi DS (2019) Biochar-induced changes in metal mobility and uptake by perennial plants in a ferralsol of Brazil's Atlantic forest. Biochar 1:309–324. https://doi.org/10.1007/s42773-019-00018-1

Vu DQ, Tran TM, Nguyen PD, Vu CC, Vu TK, Jensen LS (2012) Effect of biogas technology on nutrient flows for small scale and medium scale pig farms in Vietnam. Nutr Cycl Agroecosyst 94:1–13

Wadhwa M, Bakshi MPS (2016) Application of waste-derived proteins in the animal feed industry. In: Dhillon G (ed) Protein byproducts. Academic, Oxford, pp 161–192

Wallace PA, Nyameasem JK, Aboagye GA, Affedzie-Obresi S, Nkegbe K, Murray F, Botchway V, Karbo N, Leschen W, Maquart P, Clottey V (2018) Effects of replacing fishmeal with black soldier fly larval meal in the diets of grower-finishing guinea fowls reared under tropical conditions. Trop Anim Health Prod 50:1499–1507

Waller PJ, Thamsborg SM (2004) Nematode control in 'green' ruminant production systems. Trends Parasitol 20:1–8

Wang Q, Wang Z, Awasthi MK, Jiang Y, Li R, Ren X, Zhao J, Shen F, Wang M, Zhang Z (2016) Evaluation of medical stone amendment for the reduction of nitrogen loss and bioavailability of heavy metals during pig manure composting. Bioresour Technol 220:297–304

Wang S, Ma S, Shan J, Xia Y, Lin J, Yan X (2019) A 2-year study on the effect of biochar on methane and nitrous oxide emissions in an intensive rice–wheat cropping system. Biochar 1:177–186. https://doi.org/10.1007/s42773-019-00011-8

WRI World Resources Institute (2019) Tracking progress of the 2020 climate turning point. Working Paper. p 60

Yadav GS, Lal R, Meena RS (2020) Vehicular traffic effects on hydraulic properties of a crosby silt loam under a long-term no-till farming in Central Ohio, USA. Soil Tillage Res 202:104654

Zaman MA, Iqbal Z, Khan MN, Muhammad G (2012) Anthelmintic activity of an herbal formulation against gastrointestinal nematodes of sheep. Pak Vet J 32:117–121

Zhou X, Zhu H, Liu L (2010) A review: recent advances and future prospects of taxol producing endophytic fungi. Appl Microbiol Biotechnol 86:1707–1717

Earthworms for Eco-friendly Resource Efficient Agriculture

2

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Abstract

Waste production became the main concern in the era of the increasing world population. Millions of tons of waste are being generated everyday worldwide, and now, it is a big challenge for managing the financial and ecological expense of these wastes. An additional significant problem is arising from the disposal of municipal solid wastes, which cause emission of greenhouse gases. For sustainable development, a chief part of municipal wastes has biological garbage which can be converted into eco-friendly material like vermicompost (VCM) by using earthworm. Earthworm's activities increase the soil fertility by improving soil formation, soil porosity, water infiltration, decomposition of organic material, humus formation, suppression of soil-borne diseases & pests, and by promoting nutrient cycles which ultimately help in plant growth. Due to their beneficial activities, they cause the main change in soil properties; therefore, they are known as "Ecological engineer." Earthworms also act as a bioindicator. Earthworm forms a significant portion of soil invertebrate's biomass about 40–90% in different soil condition. The earthworm species have great diversity across the globe, which is the deciding factor to earthworm's potent towards soil improvement. Indian earthworms are dominant by indigenous species that contribute approximately 89% of total earthworm diversity and are represented by nine families, 67–69 genera, and 418–509 species of earthworms out of them, approximately 51 are exotic species. The present chapter highlights in depth the role of earthworm in efficient and sustainable agriculture.

Keywords

Earthworms · Ecological engineer · Efficient agriculture · Municipal wastes · Soil fertility · Sustainable development · Vermicompost

Abbreviations

Ca	Calcium
Cd	Cadmium
cm	Centimeter
CM	Compost
DNA	Deoxyribonucleic acid
GA	Gibberellic acid
ha	Hectare
HMs	Heavy metals
IAA	Indole-3-acetic acid
K	Potassium
kg	Kilograms
kPa	Kilo Pascal
m	Meter
mg	Milligrams
mm	Millimeter
Mn	Manganese
MOs	Microorganisms
N	Nitrogen
P	Phosphorus
t	Tonnes
VCM	Vermicompost
μm	Micrometer

2.1 Introduction

During the green revolution, agricultural production was increased due to the heavy use of chemical fertilizer, bringing more area under irrigation and by using improved genotypes (Meena et al. 2020a). Nevertheless, excess use of chemical fertilizers disturbs soil macro- and micro-fauna leading to the degradation of soil quality. Another problem arising from this is increasing of organic wastes, and decreasing of better quality of food. Earthworms have immense potential to effectively utilize these wastes to produce vermicompost. Therefore, the vermicompost is a biological fertilizer formed by the action of different earthworm species. This vermicomposting greatly contributes to the soil health improvement, product quality, efficient agriculture and thereafter overall sustainable development (Fadaee 2012; Jangir et al. 2016; Jakhar et al. 2017). Vermicompost not only decreases the volume of organic wastes but also has beneficial effect on soil fertility and plant growth. Therefore, it is suggested that we must use organic fertilizer (i.e., VCM) for good health practice (Sinha et al. 2010; Meena et al. 2018, 2020b).

Earthworms are an important member of soil invertebrate contributing about 40–90% of soil macro-faunal biomass except in some ecosystem (Fragoso et al. 1999b; Tondoh et al. 2007). Aristotle was the first who draw the attention towards the importance of earthworm and called them "Intestine of Earth" (Edwards and Bohlen 1992). In 1881, Darwin wrote the scientific book—"*The formation of vegetable mould through the action of worms with observation on their habits*" (Feller et al. 2003) in which he mentions, how worms help in soil formation and contribute to the nutrient cycle (Clark et al. 2009). Due to their vital benefit, he called earthworm as "Friend of Farmer" (Ismail 1997). Most of the people especially during Darwin time think earthworms were only unpleasant slimy, blind, ugly, senseless, and deep animals and only used as fish bait (Feller et al. 2003), but Darwin work creates interest in earthworm (Ismail 1997).

On the basis of size and habitat, Oligochaeta class of the phylum Annelida is distinguished into two groups: Microdrili (small, mainly aquatic worms including the terrestrial family Enchytraeidae) and Megadrili (larger, mostly terrestrial worms and their aquatic representatives) (Julka 1993). Earthworm belongs to phylum Annelida, class Oligochaeta with bilateral symmetry. These soil invertebrates are long, narrow, cylindrical, segmented, brownish-black tinge to purple. The dorsal side of the earthworm is darker than the ventral side. These biological agents live for almost 3–7 years depending on the environmental condition and earthworm species. They are cold-blooded animal breath through moist skin. They do not have an eye but are sensitive to light through photoreceptors present at their head region (Ismail 1997; Canti 2003; Sinha et al. 2010). They are hermaphrodite, but cross-fertilization takes place. During fertilization, two earthworms adhere to each other by their ventral surface. In mature earthworm, the anterior region generally from 13 to 17 segmented becomes swollen with glandular thickening which produces cocoon, this segment is known as clitellum. Cocoon passed from this anterior region and deposited into moist soil. Two to three juveniles are hatched out from each cocoon (Edwards and Bohlen 1996). Earthworm's body has 65, 14, 14, and 3% protein, carbohydrates, fat, and ash, respectively (Sinha et al. 2010). Due to highly richen in protein content, they are used as fish bait (Feller et al. 2003). Under the optimum condition of temperature, moisture, and feeding material, earthworm can multiple up to 256 earthworms in every 6 months from single earthworm (Sinha et al. 2010).

Bouche (1977) classified earthworm into epigeics, anecics, and endogeics on the basis of their feeding habits and position in the soil layer (Fig. 2.1).

There is a complex interaction between earthworm and their surrounding environment that make a challenging task for their study that we now called earthworm ecology (Bartlett et al. 2010). There are no doubt earthworms have beneficial roles for crops, but a few earthworm species may harm crops like *Polypheretima elongata* in central Taiwan (Gates 1959; Shih et al. 1999). The earthworm has a major role in ecosystem services that is why they are also called as ecological engineers. They play an essential role in the soil formation, improved soil structure, prompted nutrient cycling, water regulation, climate regulation, and pollution remediation. Earthworms ingest surrounding organic material and breakdown them into smaller particles (Blouin et al. 2013; Bajiya et al. 2017; Lakhran et al. 2017). They can engulf waste material almost equivalent to their own body weight daily (Sinha et al. 2010) and makes macroaggregates through their borrowing, consumption and egestion activities, thus, help in pedogenesis and soil development (Bartlett et al. 2010). The more carbon

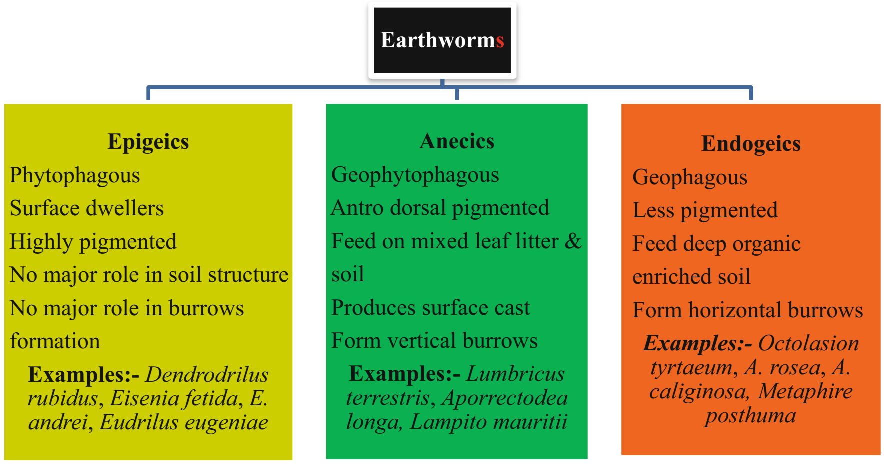


Fig. 2.1 Classification of earthworms

gets stored in these stable aggregates which improve the carbon sequestration and prevent its rapid release as greenhouse gas (Lavelle et al. 2006; Kumar et al. 2018; Meena et al. 2019). They were found to increase soil air volume 8–30%, thus refining water infiltration rate and water holding capacity (Wollny 1890; Ismail 1997).

Bioindicator has the main function of in-situ soil pollution if there is a link between deleterious change to an organism and the surrounding environment. Choice of an organism as bioindicator play a crucial part in an ecosystem, and it must be representative of almost all species inhabitant that area and the surrounding environment. The earthworm is a candidate for good bioindicator of soil pollution (Scott-Fordsmand and Weeks 2000). They have chemoreceptor which helps in searching for food. They are sensitive to the surrounding soil environment condition. They can tolerate 5–29 °C soil temperature (Sinha et al. 2010). Earthworms are susceptible to rehabilitation, biological disturbance, ecosystem perturbations (Fragoso et al. 1999a; Tondoh et al. 2007), soil humidity, soil pH, humus quality, metal contamination, pesticides, agricultural practices, and acid rain (Muys and Granval 1997). The change in number, biomass, or species richness in the natural population can be used as bioindicator. They can accumulate heavy metals (HMs) in their body tissue (Scott-Fordsmand and Weeks 2000), and particular species can accumulate specific metal contaminant. Therefore, also act as a biological indicator of metal pollution in soil (Suthar et al. 2008).

A large amount of animal and plant residues are being produced as the global human population continued to increase, which become a significant cause of pollution. Nowadays waste management becomes a serious problem. The landfill is not a solution to all problems because it may cause underground water pollution (Fadaee 2012). For efficient management, waste material must be converted into useful products. Earthworm converts biodegradable material into a different product which can be directly used by plants, thus helps in nutrient cycling. Crop residue can be converted into smaller particles about 2–3 microns by gizzard and passed from the intestine for enzymatic action. Bioreactor (gizzard + intestine) releases various enzymes like amylase, protease, lipase, cellulases, and chitinase, which bring biochemical conversion of waste material (Sinha et al. 2010). The earthworm has the efficiency to engulf a vast amount of organic material and release cast (earthworm excreta). Earthworm's cast is organic fertilizer because of rich in humus, exchangeable nitrogen (N), phosphorus (P), potassium (K), manganese (Mn), calcium (Ca) and other beneficial microorganisms (MOs) (phosphate solubilizing bacteria, N-fixing bacteria, *Pseudomonas,* actinomycetes), and plant growth hormone (gibberellins, auxin, cytokinin) (Ismail 1997; Adhikary 2012). During the passing of organic waste through earthworm's gut, MOs get incorporated in this ingested waste and released with the cast. These MOs further help in the breakdown of organic material. Finally, this waste is converted to VCM, which is also known as "organic gold" (Sinha et al. 2010).

2.2 Diversity of Soil Earthworms

Most of the ecosystems are highly rich in soil fauna which is distinguished by their body size. Soil macro-fauna have body size larger than 2 mm (millimeter) and mesofauna having a size between 100 μm (micrometer) and 2 mm; whereas microfauna has a size less than 100 μm (Barrios 2007; Wissuwa et al. 2012; Wu and Wang 2019). Among them, soil macro-fauna (invertebrates) like earthworms, root herbivorous insects, ants, and termites play the most crucial function in the sustainability of agroecosystem (Bottinelli et al. 2015). Here we only study the diversity of earthworm because of our main concern in this chapter for earthworms (Table 2.1). Diversity and composition of earthworms vary from site to another site over a broad range, but they are mainly abundant in the tropical region (Fragoso et al. 1999b; Decaëns et al. 2004). All over the world almost 4200–4400 of oligochaetes of 20 families are noticed, out of them about 3200 species are magadrili (e.g. earthworm), and almost 280 species belong to microdrili (Munnoli et al. 2010; Goswami and Mondal 2015). The Indian subcontinent has bulk of oligochaete fauna in which indigenous species contribute approximately 89% of total earthworm diversity and are represented by nine families, 67–69 genera, and 418–509 species of earthworms (Munnoli et al. 2010; Dash and Saxena 2012; Sharma and Poonam 2014) of which approximately 51 are exotic species. The Western Ghats, Eastern Himalayas, and Western Himalayas contribute 53, 26, and 12% earthworm species, respectively (Paliwal and Julka 2005; Dash and Saxena 2012).

2.3 Beneficial Attributes of Earthworms

Soil organism lives in the soil as well as they are part of the soil, therefore, influences the soil properties such as aeration, gaseous composition, and hydrology. Earthworms improve soil structure through modification of different soil properties that are finally essential for improving soil richness and primary production for any ecosystem (Brussaard 1997). Earthworms have many benefits (Fig. 2.2), and due to

Table 2.1 Diversity of Indian earthworm

S. No.	Family	Number of species	Name of species	Place of study	References
1.	Monilgastridae	7	*Drawida paradox, D.* sp. *(nr. thurstoni Gates), D. ampullacea, D.* sp.1, *D.* sp.2, *D. kanarensis, D. sulcata*	Western Ghats	Blanchart and Julka (1997)
	Megascolecidae	3	*Megascolex* sp., *Perionyx* sp., *Lennoscolex* sp.		
	Octachaetidae	18	*Hoplochaetella* sp.1, *H.* sp.2, *H. sanvordemensis, Hoplochaetelia H. Gates, Konkadrilus tirthahalliensis, K.* sp.1, *K.* sp.2, *K.* sp.3, *Genus A* sp.1,*Genus* sp.2, *Genus B*.sp.1, *Genus C* sp.1, *Genus C* sp.2, *Genus C* sp.3, *Mallehtdla indica, Wahoscolex* sp., *Karmiella karnatakensis, Karmiella* sp.1		
2.	Glossoscolecidae Megascolecidae Ocnerodrilidae Octochaetidae	9	*Ramiella bishambari, Dichogaster bolaui, Amynthas morrisi, Octochaetona paliensis, Perionyx sansibaricus, Pontoscolex corethrurus, Ocnerodrilus occidentalis, L. mauritii, M. posthuma*	Arid regions of Jodhpur, Rajasthan	Tripathi and Bhardwaj (2004)
3.	Moniligastridae, Lumbricidae Almidae Ocnerodrilidae Acanthodrilidae Octochaetidae Megascolecidae	51	*Dendrodrilus rubidus, Drawida japonica, D. nepalensis, Allolobophora eiseni, A. parva, Eisenia fetida, Aporrectodea caliginosa,*	Western Himalaya states	Paliwal and Julka (2005)

(continued)

Table 2.1 (continued)

S. No.	Family	Number of species	Name of species	Place of study	References
			Aporrectodea trapezoides, Aporrectodea rosea, Lumbricus castaneus, L. terrestris, Dendrobaena hortensis, D. octaedra, Octolasion cyaneum, O. tyrtaeum, Glyphidrilus sp., *Malabaria levis, O. occidentalis, Eiseniella tetraedra, Thatonia exilis, T. gracilis, Microscolex phosphoreus, Plutellus sadhupulensis, D. bolaui, Eutyphoeus annandalei, E. incommodus, E. nainianus, E. nicholsoni, E.orientalis, E. pharpingianus, E. waltoni, Lennogaster chittagongensis, L. parvus, L. pusillus, L. yeicus, R. bishambari, Amynthas alexandri, A. corticis, A. gracilis, A. morrisi, Metaphire anomala, M. birmanica, M. houlleti, M. posthuma, Perionyx bainii, P. barotensis, Perionyx excavatus, P. nainianus, P. sansibaricus, P. simlaensis*		
4.	Moniligastridae Glossocolecida Megascolecidae Acanthodrilidae Octochaetidae Eudrilidae	10	*Octochaetona serrata, O. barnesi, P. excavatus, E. eugeniae, Pontodrilus bermudensis, L. mauritii, P. corethrurus,*	Pondicherry region	Sathianarayanan and Khan (2006)

			Drawida willsi, D. lamella, D. scanden		
5.	Eudrilidae Lumbricidae, Megascolecidae Ocnerodrilidae Octochaetidae Moniligastridae	30	*E. eugeniae, A. caliginosa, A. parva, D. rubidus, E. fetida, Octolasion tyrtaeum, A. alexandri, A. corticis, A. gracilis, A. morrisi, L. mauritii, Metaphire houlleti, M. posthuma, Polypheretima elongata, P. bainii, P. barotensis, P. excavatus, P. sansibaricus, P. simlaensis, Gordiodrilus elegans, O. occidentalis, D. bolaui, Eutyphoeus ibrahimi, Eutyphoeus incommodus, E. waltoni, L. chittagongensis, L. pusillus, O. beatrix, R. bishambari, D. japonica*	Northern Indian states	Dhiman and Battish (2006)
6.	Octochaetidae	6	*A. alexandri, Eutyphoeus oreintalis, E. incommodus, E. waltoni, E. nicholsoni, Octochaetona Beatrix*	Rajaji National Park, Uttarakhand (foothills of Shivalik Himalaya)	Joshi and Aga (2009)
7.	Moniligastridae Lumbricidae, Octochaetidae, Megascolecidae	9	*Drawida nepalensis, O. tyrtaeum, E. incommodus, E. orientalis, E. pharpingianus, E. nicholsoni, O. beatrix, E. waltoni, L. mauritii*	Doon valley of Western Himalayan, Uttarakhand	Deepshikha (2011)
8.	Glossoscolecidae, Megascolecidae, Lumbricidae, Ocnerodrilidae, Octochaetidae		*P. corethrurus, L. mauritii, A. parva, M. posthuma, D. bolaui, O. paliensis, A. morrisi, R. bishambari, O. occidentalis, Malabaria* sp., *P. sansibaricus*	Semiarid area, and western arid, Rajasthan	Suthar (2011)

(continued)

Table 2.1 (continued)

S. No.	Family	Number of species	Name of species	Place of study	References
9.	Moniligastridae, Megascolecidae, Lumbricidae	8	*A. caliginosa*, *Octolasion cyaneum*, *E. fetida*, *O. cyaneum*, *A. rosea*, *A. trapezoides*, *A. corticis*, *D. japonica*	Kashmir Valley, J&K	Najar and Khan (2011)
10.	Moniligastridae, Megascolecidae, Lumbricidae, Octochaetidae	8	*Metaphire birmanica*, *A. alexandri*, *P. excavatus*, *D. nepalensis*, *Bimastos parvus*, *M. anomala*, *O. beatrix*, *Lennogaster pusillus*	Bhiri-Banswara, Chamoli, central Himalaya	Bhadauria et al. (2012)
11.		30	*Perionyx sansibaricus*, *P. excavatus*, *O. beatrix*, *L. pusillus*, *R. bishambari*, *Eutyphoeus incommodus*, *E. michaelseni*, *E. waltoni*, *D. nepalensis*, *Thatonia gracilis*, *D. bolaui*, *A. alexandri*, *A. corticis*, *A. morrisi*, *M. houlleti*, *M. posthuma*, *D. japonica*, *O. occidentalis*, *A. parva*, *A. trapezoides*, *A. rosea*, *E. fetida*, *O. tyrtaeum*, *Perionyx* (4 species), *Eutyphoeus* (2 species), *Plutellus* sp.	Western Himalaya	Dash and Saxena (2012)
		19	*L. mauritii*, *P. excavatus*, *D. nepalensis*, *Dichogaster affinis*, *D. bolaui*, *A. alexandri*, *A. corticis*, *A. morrisi*, *M. houlleti*,	Eastern Himalaya	

			M. posthuma, P. elongata, P. corethrurus, A. parva, A. trapezoides, A. rosea, E. fetida, O. tyrtaeum, Tonoscolex sp., *Kanchuria* sp.,		
		36	*L. Mauritii, P. excavatus, P. sansibaricus, O. beatrix, Octochaetona palniensis, R. bishambari, D. affinis, D. bolaui, Amynthas alexandri, A. corticis, A. morrisi, M. houlleti, M. posthuma, P. elongata, P. corethrurus, O. occidentalis, A. parva, A. trapezoides, A. rosea, E. fetida, O. tyrtaeum, Curgiona* sp., *Kotegeharia* sp., *Mallehulla* sp., *Priodochaeta* sp., *Karmiella* sp., *Troyia* sp., *Comarodrilus* sp., *Chaetocotoides* sp., *Parryodrilus* sp., *Dashiella* sp., *Moniligaster* sp., *Celeriella* sp., *Lampito* sp., *Travoscolides* sp., *Wahoscolex* sp.	Western Ghats	
12.	Acanthodrilidae, Glossoscolecidae, Moniligastridae, Megascolecidae, Octochaetidae		*Argilophilus* sp., *Perionyx ceylanensis, P. corethrurus, Drawida grandis, D. parva, D. travancorensis, D. sulcata, D. nr. parambikulamana, D.* sp., *D. robusta, Priodochaeta pellucid, A. corticis*	Nilgiri biosphere reserve, Western Ghats	Chandran et al. (2012)

(continued)

Table 2.1 (continued)

S. No.	Family	Number of species	Name of species	Place of study	References
13.	Megascolecidae, Octochaetidae, Lumbricidae		*M. posthuma, A. morrisi, L. mauritii, E. incommodus, O. beatrix, Bimastos parvus*	GNDU, Amritsar, Punjab	Mohan (2013)
14.	Moniligastridae, Megascolecidae, Octochaetidae, Lumbricidae	18	*Amynthas robustus, A. morrisi, M. posthuma, L. mauritii, D. bolaui, D. nepalensis, E. incommodus, E. waltoni, E. nicholsoni, O. occidentalis, O. beatrix, Bimastos parvus, R. bishambari, L. pusillus, M. birmanica, M. houlleti, P. simlaensis*	Haryana	Sharma and Poonam (2014), Bhardwaj and Sharma (2016), and Garg and Julka (2016)
15.	Moniligastridae, Megascolecidae, Almidae, Glossoscolecidae, Lumbricidae, Ocnerodrilidae	17	*M. posthuma, D. nepalensis, Drawida* sp.1, *Drawida* sp.2, *G. elegans, Glyphidrilus gangeticus, Eutyphoeus* sp., *P. excavatus, P. annandalei, P.* sp., *Amynthas diffringens, A. alexandri, L. mauritii, E. fetida, Eisenia* sp., *P. corethrurus, Dichogaster saliens*	Assam, an indo-Burma biodiversity hotspot.	Rajkhowa et al. (2015)
16.	Megascolecidae, Octochaetidae	6	*M. posthuma, P. excavatus, A. diffringens, L. mauritii, D. bolaui, E. orientalis*	West Bengal	Goswami and Mondal (2015)
17.	Naidae, Tubificidae, Lumbricidae, Megascolecidae, Octochaetidae, Moniligastridae	51	*Aulophorus tonkinensis, Branchiodrilus hortensis, Dero limosa, D. bolaui, Nais communis,*	Uttar Pradesh	Verma and Bharti (2010); Prakash (2017)

			Nais obtuse, N. inaequalis, Pristina aequiseta, Haemonais laurentii, Aulodrilus kashi, A. stephensoni, Branchiura sowerbyi, Allolbophora papillatus, Glyphidrilus tuberosus, G. papillatus, P. corethrurus, E. fetida, A. morrisi, L. mauritii, M. posthuma, M. houlleti, M. anomala, M. birmanica, M. elongata, P. excavatus, P. sansibaricus, P. elongata, O. occidentalis, Malabaria sulcata, L. pusillus, Pellogaster bengalensis, E. incommodus, E. mohammedi, E. waltoni, E. masoni, E. pharpingianus, E. orientalis, E. paivai, E. nicholsoni, E. gigas, Eudichogaster ashworthi, E. parvus, E. prashadi, R. bishambari, O. fermori, O. paliensis, O. beatrix, O. surensis, D. calebi, D. willsi		

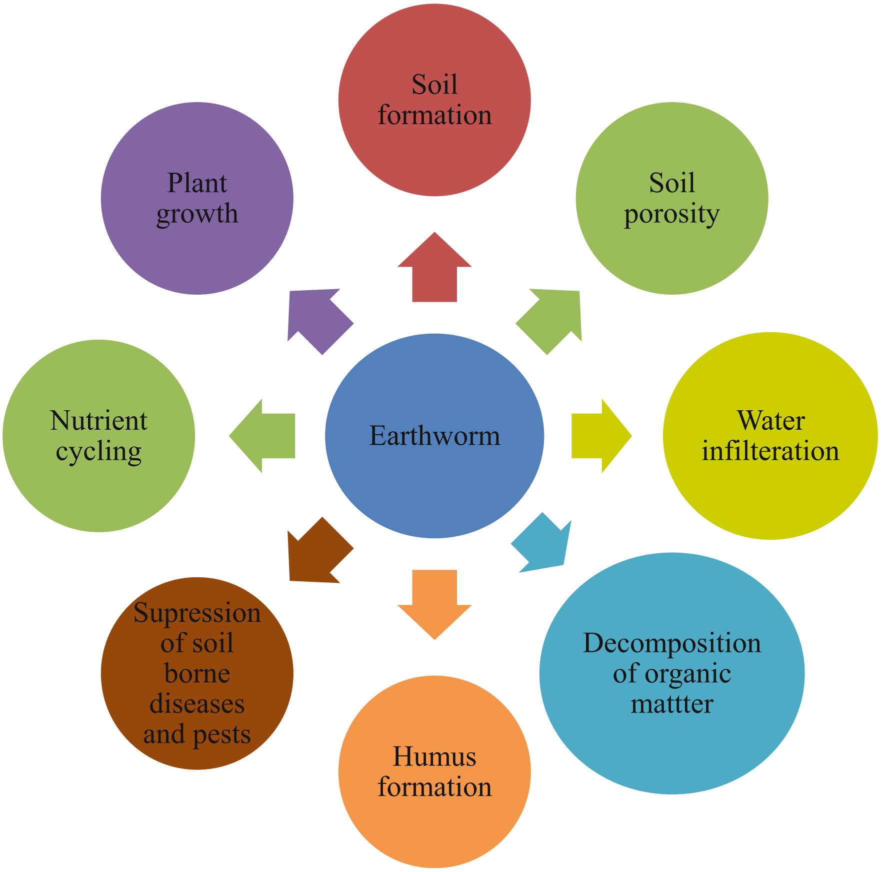


Fig. 2.2 Benefit of earthworms

that, Darwin and Aristotle, respectively, called them as "friend of farmer" and "intestine of earth" (Ismail 1997).

2.3.1 Soil Formation

Soil formation is a long-time process which is influenced by surrounding environment condition and parent material. Earthworm helps in soil development through different ecosystem services like mineral weathering, humus formation, vermiform soil formation, and mixing of organic material with soil to create water-stable aggregate (Pop 1998; Blouin et al. 2013). Darwin (1881) noticed that earthworm causes downward movement of small stones and gravel as well as additionally caused annual deposition of 10 tonnes (t) of fine soil to the soil surface. Sinha et al. (2010) also observed that three million earthworms in one-acre soil could transport 8–10 t of topsoil to the surface within 1 year. The “vermiform soil” contributes about 50% or more in the “A” horizon and 25% in the “B” horizon (Pop 1998; Blouin et al. 2013). Because earthworms ingest a huge amount of organic material and organically enriched soil, and finally release cast in the soil where they are inhabitant. These casts not only help in soil formation but also improve the soil structure and provide resistance to soil erosion (Le Bayon et al. 2002). These casts have MOs with some mucus, thus form water-stable aggregates (organo-mineral complexes) (Lavelle et al. 2006). The water-stable aggregate is deposited either on the surface or within the soil depending upon environmental condition and earthworm species ultimately help in soil formation (Le Bayon et al. 2002). In a temperate climate, earthworm’s cast may be form 2 to 10 kg m^{-1} (kilograms per meter) soil that is corresponding to 5–25 mm thick soil layer (Bertrand et al. 2015). Jouquet et al. (2008) observed that *Amynthas khami* (anecic earthworm species) released 8–22 cast kg m^{-2} on the soil surface that could create 5–15 centimeter (cm) deep soil horizon (Bottinelli et al. 2015).

2.3.2 Soil Porosity

Compaction of soil is a serious problem in agriculture practice associated with running of heavy machinery on soil surface continuously. Due to soil compaction air volume can be reduced from 12% to 7% (Hansen 1996; Jégou et al. 2002). It is well understood that the earthworm burrow system plays the most important contribution in increasing soil porosity by changing physical, chemical, and biological properties of soil. Soil pores formed by earthworm influence decomposition of organic material, water infiltration rate, distribution of nutrient, and gas exchange during the plant respiration and thus promote root growth. Burrow system formed by earthworm also influences the microbial action and movement of other soil organisms in their surrounding environment. It is also observed that to improve the plant yield in organic farming; there is a need to avoid the soil compaction rather than to increase manure (Langmaack et al. 1999; Jégou et al. 2002). Depending on the ecological group (i.e., epigeic, anecic, and endogeic), earthworms created macropores 2–11 mm in diameter. Epigeic earthworms have no major contribution to soil porosity. However, a diameter of endogeic earthworm’s pores ranging between 2 and 5 mm and anecic earthworms form large vertical orientated, semi-permanent dig (larger than 5 mm diameter) that can extend greater than 2 m in soil depth. Thus, endogeic and anecic species have a major contribution in soil porosity (Langmaack et al. 1999; Fischer et al. 2014).

2.3.3 Water Infiltration

Water infiltration in the soil is mainly dependent upon the soil porosity than the other soil properties (Gupta and Kumar 2018). It was also expected that the spatial distribution of plant roots is controlled by macropores (Dahiya et al. 2018). Large macropores play a primary role in the regulation of water infiltration (Bottinelli et al. 2015). Water infiltration rate depends upon the geometry (diameter and length), and spatial properties of earthworm's burrow system (Chan 2004). In dye infiltration experiment showed that only 53% macropores were able to conduct water and rest may be blocked due to casts and plant roots (Chan 2004). Shuster et al. (2002) found that water percolation rate is defiantly associated with earthworm's biomass, burrow surface area and its length. For examples, earthworm presence (10 years) increased water infiltration rate from 15 to 27 mm h^{-1} (Clements et al. 1991). Soil pore formed by earthworm is responsible for two- to tenfold increment of water infiltration (Lee 1985; Chan 2004), and in the United States, 50% water penetration increment was observed which is equivalent to benefit given by three farmers (8 h day^{-1}) all over the year with using manure (Li et al. 2010; Sinha et al. 2010). Water infiltration by anecic earthworms reduced the soil erosion by up to 50% (Shuster et al. 2002).

2.3.4 Organic Matter Decomposition

The organic matter decomposition represents the most important catabolic process of photosynthesis performed by soil organisms (Jangir et al. 2017, 2019). It is the conversion of complex organic material in to simpler one by soil organism (Barrios 2007). Earthworms are involved in the breakdown of soil organic material. They break down large soil particles, plant litter, and any other organic material into small particles, as a result, it increased the surface area for microbial degradation. Microbial number and activities were increased when organic material passes through the earthworm's gut that helps in its degradation. Earthworm's cast is rich in clay, glycoprotein, polysaccharides, bacteria, fungi, and many other MOs which increased the efficiency for microbial degradation (Edwards et al. 1996; Furlong et al. 2002). Brussaard (1997) observed that 90% of organic material decomposition caused by MOs such as bacteria, fungi, etc. Water-soluble nutrients (like Ca, Mg, K) are also increased during and after the passage through the earthworm's gut (Carpenter et al. 2007). Due to earthworm, rearrangement of organo-mineral material occurred through decomposition, and finally, they provide a nutrient that can be easily absorbed by the plants (Araujo et al. 2004). There are mainly four mechanisms involved for earthworm and microbe's interaction that help in the breakdown of organic material (Fig. 2.3) (Brown 1995; Bertrand et al. 2015).

2.3.5 Humus Formation

The process of humus formation is slow in which darkening of soil mold occurs primarily by chemical reactions and microbial activity (Edwards et al. 2010). Humic acid is the major part of humus which is characterized by dark-colored, alkali-soluble, and acid-insoluble organic material. Organic materials can form the humus within a few months depending upon the environmental condition and earthworm species (Canellas et al. 2002). For examples; in vermicomposting, earthworms

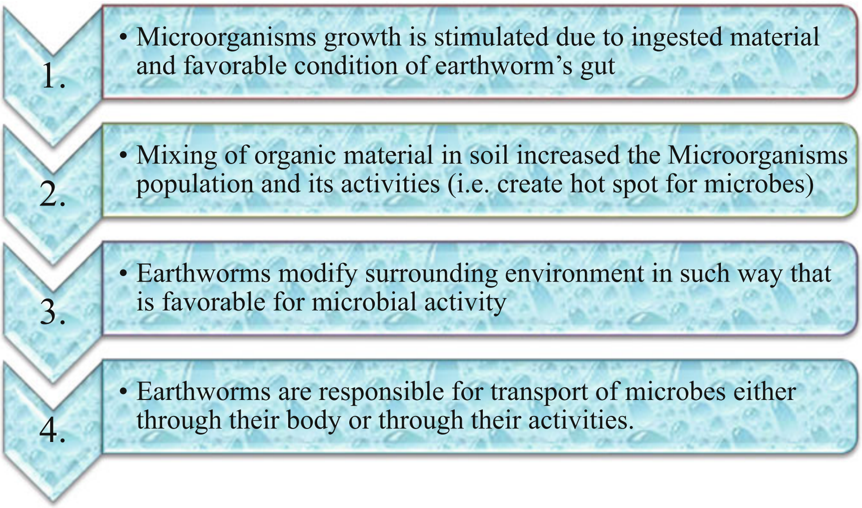


Fig. 2.3 Mechanisms involved in organic matter decomposition by earthworm

provide a favorable condition that leads to an increase of 40–60% humus substances as compared to compost (CM) (Dominguez et al. 1997). Humification rate in the soil is controlled by earthworm's activities such as mixing of leaf litter, burrowing, feeding habit, casting, and interaction with microbes (Edwards et al. 2010). As compared with other manure, earthworm's cast has higher humic acid (Li et al. 2010). Earthworms ingest 12 t of soil/organic material per hectare per year, as a result, turning 18 t of soil per hectare per year. Thus, it was producing 2 inches humic fertile layer that is essential for plant health (Sinha et al. 2010). In the absence of humus, plant growth is retarded (Li et al. 2010). Transferable auxin was noticed in the macrostructure of composted humus that suggests that hormonal activities in humus (Canellas et al. 2002).

2.3.6 Suppression of Soil-Borne Diseases and Pests

The occurrence of soil-borne diseases and pests in a natural ecosystem is rare, but it is common in agriculture. Plant-parasitic nematodes are a significant problem in agricultural which reduce the yield of plant and this cause economic loss worth over 100 billion annually (Barker 2003). Earthworms indirectly control the nematodes population (Räty and Huhta 2003; Blouin et al. 2005), also in the presence of earthworms, the expected inhibition of plant photosynthesis is suppressed, and root biomass was not affected by a nematode. External cysts on rice (*Oryza sativa*) roots formed by *Heterodera sacchari* but in the presence of earthworm suppression of infestation up to 82% was observed (Blouin et al. 2005), e.g. *Reginaldia omodeoi* (formally known as *Millsonia anomala*) (Bertrand et al. 2015). The severity because of the soil-borne fungal pathogen also gets reduced in the presence of earthworms, e.g. *A. rosea* and *A. trapezoides* (Stephens and Davoren 1997; Bertrand et al. 2015).

2.3.7 Nutrient Cycling

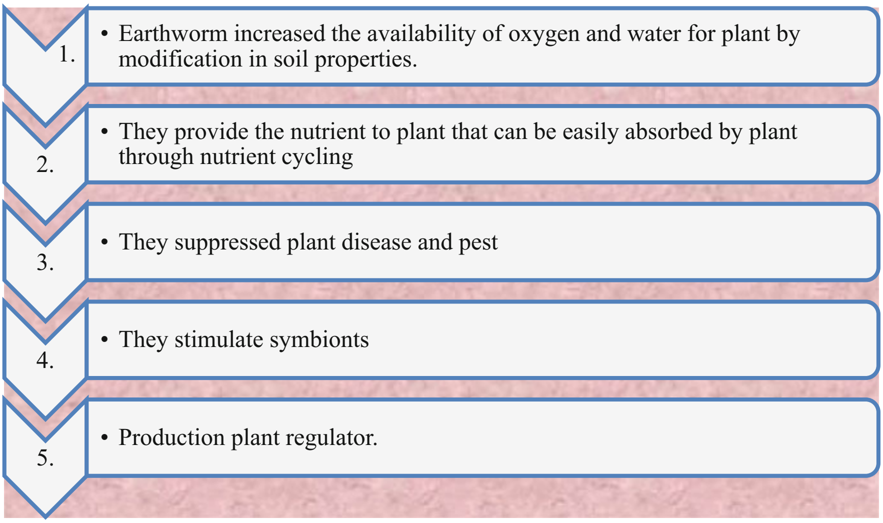
Nutrient cycling is a very difficult task to measure the accurate flow and transformation of nutrient from the soil (Kakraliya et al. 2017a, b; Kumar et al. 2020). Therefore, to evaluate the potential contribution of earthworms to nutrient cycling in an ecosystem, data from the laboratory has been combined with the result of biomass and climatic condition (Haimi and Huhta 1990). After the digestion, some nutrient flows in the environment whereas some remain in the soil. Earthworms modified the complex nutrient into more simple reusable form for the plant, especially N compound. Earthworms contribute in N mineralization directly through their dead body and metabolic waste (like cast and mucus; that may contain ammonium, allantoin) as well as indirectly through changing soil properties, fragmentation, and interactions of organic material with MOs (Blouin et al. 2013). Carpenter et al. (2007) studied that, 300 earthworms m^{-2} could have 14 kg N ha^{-1}(hectare) and most of the N is present in the 0–15 cm soil layer (Bertrand et al. 2015).

2.3.8 Plant Growth

In several ways, soil invertebrates have found to affect plant growth by influencing plant competition and susceptibility to herbivores. Earthworm burrows system is one of the belowground associations that affect plant growth (Meysman et al. 2006). Plant uses earthworms burrow to grow its root and also for respiration. Earthworm's activities increased the nutrient turnover for plant growth (Lavelle et al. 1998). For examples, *R. omodeoi* presences in soil increased shoot biomass and carbon dioxide (CO_2) assimilation by 40% and 13%, respectively (Blouin et al. 2007). Earthworm helps to improve the nodulation process of legumes led by *Rhizobium* species (Bertrand et al. 2015). Five mechanisms are responsible for plant growth by earthworms (Fig. 2.4) (Brown et al. 2004; Bertrand et al. 2015).

2.4 Earthworm as Agent for Ecological Engineer

Ecological engineers are those who have directly and indirectly affect physical, chemical, and biological properties of the surrounding soil environment (Fig. 2.5). In other words, the presence of organism affects the surrounding abiotic environment, but real ecological engineers are those which impart themselves in a way that their absence or presence has a significant effect on ecological services. In short, earthworm as an ecological engineer has direct or indirect effect on surrounding abiotic and biotic factor of soil (Coleman and Williams 2002; Meysman et al. 2006).



1. Earthworm increased the availability of oxygen and water for plant by modification in soil properties.
2. They provide the nutrient to plant that can be easily absorbed by plant through nutrient cycling
3. They suppressed plant disease and pest
4. They stimulate symbionts
5. Production plant regulator.

Fig. 2.4 Mechanisms involved in plant growth by earthworm

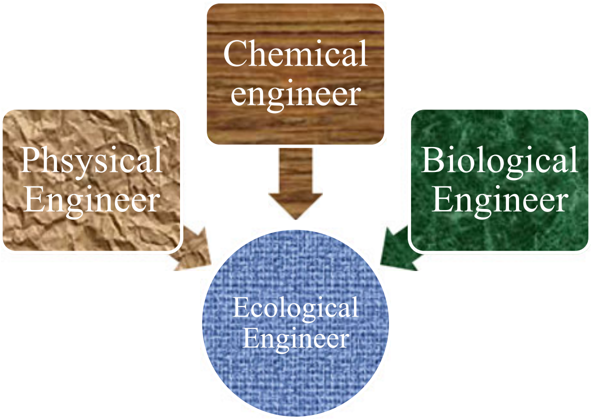


Fig. 2.5 Component of ecological engineer

Over 600 million years, earthworms are considered as "ecosystem engineers" due to their vital role to sustain the soil ecosystem (Sinha et al. 2010).

2.4.1 Earthworm as Physical Engineer

The earthworms form the horizontal and vertical burrows; thus, increase soil porosity, water infiltration rate and reduce soil compaction. They also carried out the physical breakdown of organic materials (Carpenter et al. 2007; Sinha et al. 2010). Earthworm's gizzard is capable for the breakdown of the ingested food material up to 2–4 micron and increases the surface area for the microbial action in its intestine and in the soil where they are inhabitant (Drilosphere) (Sinha et al. 2010; Fusaro et al. 2018).

2.4.2 Earthworm as Chemical Engineer

As a chemical engineer, enzymatic action was done by the earthworm. Biochemical conversion occurred by different enzymes like amylase, cellulase, protease, lipases, and chitinases and that convert complex organic materials into more unaffected digestible materials. Chemical degradation via enzymes was also due to enzymes produced by bacteria, fungi, protozoa, etc., The intestine of earthworm further mixed this digested organic material with microflora. Therefore, we can say both gizzard and intestine work as "bioreactor." Thus; they also act as a biochemical engineer (Barrios 2007; Sinha et al. 2010).

2.4.3 Earthworm as Biological Engineer

The earthworms act as a biological engineer because of their interactions (symbiosis) with soil MOs, such as bacteria and fungi, including VAM (vesicular-arbuscular mycorrhizae). Earthworm's gut has numerous beneficial MOs for plant growth, and they are released in earthworm's cast. These cast's MOs further help in the digestion of organic material (Rabatin and Stinner 1988; Fusaro et al. 2018; Sinha et al. 2010).

It is a crucial point to notice here that mineral weathering may be legend acted mechanism due to both earthworm's enzyme and by microbial activities. Hence, it is a difficult task to measure the contribution of earthworms in this weathering as the survival of earthworm dependence on MOs (Carpenter et al. 2007; Fusaro et al. 2018).

2.5 Composting and Vermicomposting

Millions of tonnes of waste are generated every day, and we are facing the environment cost and socio-economic cost of managing this waste. This waste has primary biodegradable organic material that must be reused for efficient agriculture. By vermicomposting and composting, we can achieve the goals of efficient agriculture and overall sustainable development. There are some similarities (Fig. 2.6) and dissimilarities (Table 2.2) between vermicomposting and composting, but overall, vermicomposting had better results than composting (Loehr et al. 1984; Edwards 1998; Sinha et al. 2010).

Vermicompost is an environment-friendly, socially acceptable, and economically viable odorless process in which waste organic materials are digested in the presence of earthworms (Sinha et al. 2010). Depending upon the organic material used for vermicomposting, the physio-chemical composition of VCM varies, i.e. pH

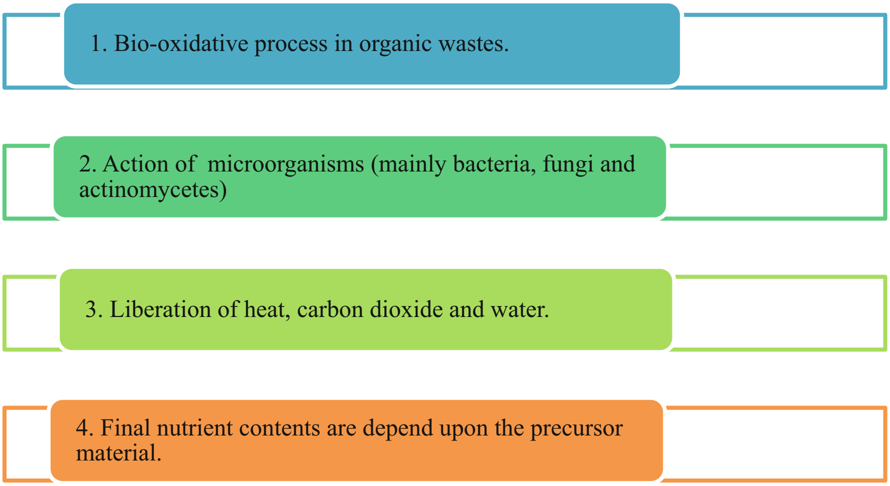


Fig. 2.6 Similarity between composting and vermicomposting (Tognetti et al. 2005)

Table 2.2 Dissimilarities between composting and vermicomposting (Arancon et al. 2004; Tognetti et al. 2005)

S. No.	Compost	Vermicompost
1.	Due to the action of microorganisms	Due to couple action of earthworms and microorganisms
2.	Involvement of the thermophilic stage (45 to 65 °C)	Involvement of mesophilic stage (temperatures above 35 °C may kill earthworms)
3.	Mainly turning and aeration processes occur	Mainly turning, fragmentation, and aeration processes occur
4.	Moisture content is 40 to 60%	Moisture content is 70–90%
5.	Pathogens are effectively reduced in product	Pathogens may or may not be effectively reduced in product
6.	Less microbial activities and nutrient contents	Higher microbial activities and nutrient contents
7.	The final product is somewhat in compact clumps	The final product is homogenous
8.	It is less strongly humified	It is more strongly humified

(6.5–7.5), moisture content (60–70%), aeration (50%), temperature (18–35 °C), N (0.8–3.0%), P (0.5–1.7%), and K content (0.5–1.6%) (Ansari et al. 2020). In composting, earthworms are not involved, and self-heating phase and fewer humidity (3–6%) may be the reason for less bacterial diversity in it as compared to VCM (Fracchia et al. 2006).

Vermicomposting of buffalo dung led to the better microbial processed end product as compared to composting (Ngo et al. 2011). There is also quantitatively more functional microbial diversity in the presence of earthworm, and this is due to the modification of physicochemical properties of waste material as a result of this it

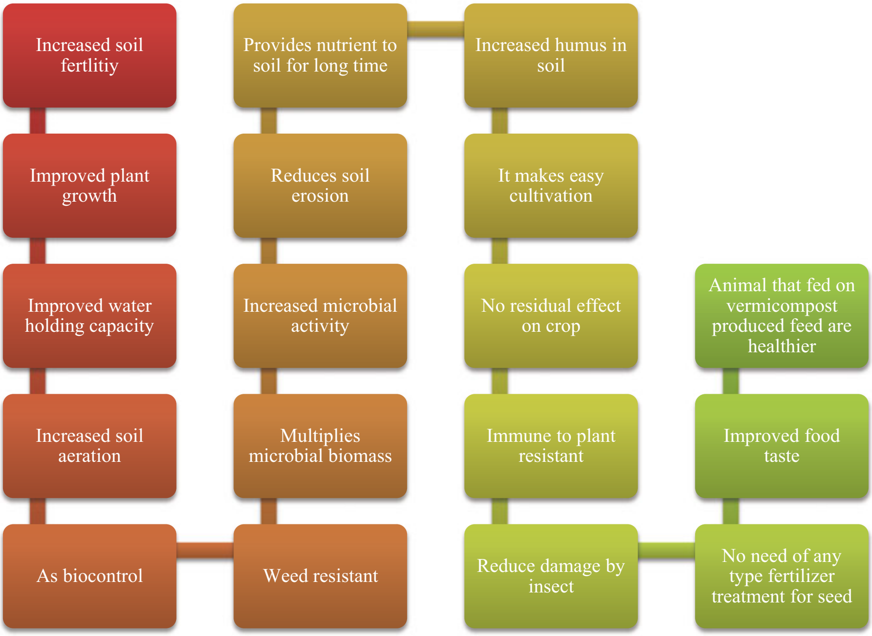


Fig. 2.7 Advantages of vermicompost

provides favorable microhabitats for microbial action (Vivas et al. 2009). Dominant bacterial communities in composting material were *Firmicutes* and *Actinobacteria,* whereas in VCM were *Chloroflexi*, *Bacteroidetes*, and *Gemmatimonadetes*. Generally, CM has spore-forming bacteria that allow them to be active in the thermophilic stage (Fracchia et al. 2006; Vivas et al. 2009).

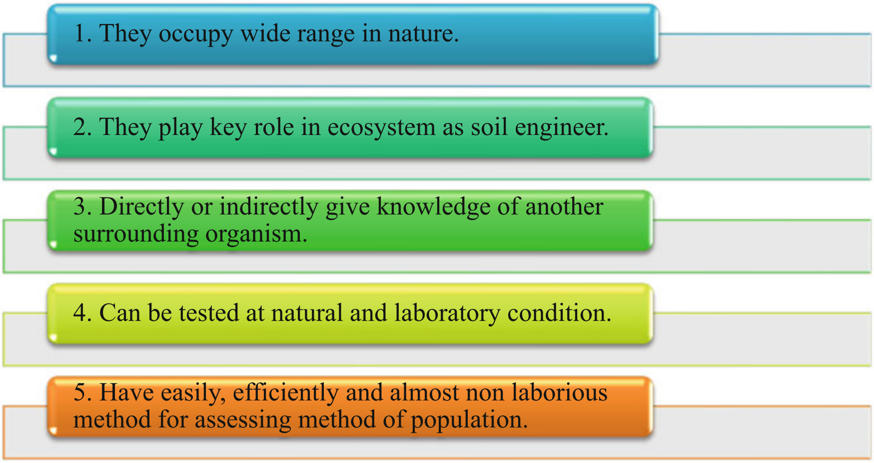
Vivas et al. (2009) observed that faster mineralization of olive-mill waste occurs in VCM than CM. Increment of phytohormone (milligrams—mg kg^{-1}) in VCM was recorded as indole-3-acetic acid (IAA) (7.37), kinetin (2.8), and gibberellic acid-3 (GA)(5.7); whereas, in composting as IAA (5.84), kinetin (2.7), and GA-3 (4.0). It may be associated with earthworm's microbial population in its gut (Ravindran et al. 2016). Vermicompost could also be used as an alternative to inorganic fertilizers, whereas there is a limitation of using CM when we expected a short-term effect on plant growth (Jouquet et al. 2011). Numerous advantages of vermicomposting to the soil and plant health are diagrammatically represented in Fig. 2.7 (Munnoli et al. 2010).

2.6 Earthworm for Bioremediation

Bioremediation is a novel method of waste management for sustainable development. Bioremediation using microbes, economically and environmentally are considering safe (Gupta and Prakash 2020). The earthworm and soil microbes play a vital role in bioremediation wastes management because of their synergistic association (Sun et al. 2020). Earthworm helps in soil remediation by making the lining of burrows (*L. terrestris*), which reduces vertical transport of pesticides, by facilitating metal uptake by plants (phytoremediation), by inducing pesticide-detoxification enzymes in soil, and contribution in the breakdown of organic pollutants (Sanchez-Hernandez et al. 2019). Earthworms were also utilized for dispersing of MOs which can degrade the pollutant. For examples, bio-augmented polychlorinated biphenyl (PCB) degrading MOs were dispersed by *Pheretima hawayana,* and due to that 55% contaminant were removed than control (39%) having no earthworm (Singer et al. 2001). The presence of *Hyperiodrilus africanus* earthworm has significantly reduced the total petroleum hydrocarbon (84.99%), benzene (91.65%), ethylbenzene (100%), xylene (100%), and toluene (100%) from crude oil contaminated soil (Ekperusi and Aigbodion 2015). Similarly, *E. fetida* accelerates the degradation of oxytetracycline and its main metabolites (4-epi-oxytetracycline and 2-acetyl-2-decarboxamido-oxytetracycline) by remediating microbes (Liu et al. 2020). Huang et al. (2020) studied that sludge-VCM formed by *E. fetida* reduced the antibiotic resistance gene encoding plasmids and integrins as well as also reduced the total human pathogenic bacteria.

2.7 Ecosystem Indicator

Assessment of soil quality defined as the ability of soil to provide ecological services sustainably (Pérès et al. 2011). Soil invertebrates are an essential organism of soil and any change in soil quality directly affects them. Therefore, they can be used as an ecosystem indicator (Lavelle et al. 2006). Some of the key-features calling of earthworms as bioindicator are highlighted in Fig. 2.8 (Edwards et al. 1996).



1. They occupy wide range in nature.
2. They play key role in ecosystem as soil engineer.
3. Directly or indirectly give knowledge of another surrounding organism.
4. Can be tested at natural and laboratory condition.
5. Have easily, efficiently and almost non laborious method for assessing method of population.

Fig. 2.8 Key feature which makes earthworms as bioindicator

Various changes in earthworm can be used as ecosystem indicators such as earthworm communities (abundances and activities) (Suthar 2009), bioaccumulation in casts and tissues (Suthar et al. 2008), and histopathological changes (Shi et al. 2020). Earthworm abundance and activities can act as a bioindicator for management practices of agricultural soil. For example; at the different study site, it was found that a maximum number of earthworms are present in integrated farming (100%), followed by in organically managed soil (70%) and minimum in conventional agricultural soil (Suthar 2009). Shi et al. (2020) studied that histopathological change like damage of microvilli and cuticle are early warning bioindicator of pesticide (endosulfan) contamination. Change in sperm parameter can be used as a sensitive biomarker to indicate metal toxicants in soil (Sinkakarimi et al. 2020b). *Eisenia fetida* is proved less sensitive than *A. rosea* and *A. trapezoides* to cadmium (Cd) and lead contamination. This difference in sensitivities suggests that native earthworm species should be considered for toxicant (Sinkakarimi et al. 2020a).

2.8 Declining Earthworm Population: A Challenge to Sustainability

The promotion of usages of chemical fertilizers during the period of green revolution improved the crop growth, but their unsustainable use reduced soil fertility (Varma et al. 2017; Meena et al. 2017; Sharma et al. 2019). After sometime saturation point of soil will come and we will not be able to get yield by these chemicals. Then we need to follow the advanced techniques for sustainable development (Densilin et al. 2011). In this line, Sinha et al. (2010) developed some by using earthworms like the vermicomposting technology, the vermi-filtration technology, the vermi-remediation technology, the vermi-agro-production technology, and the vermi-industrial production technology.

We already studied in detail different direct and indirect benefit of earthworm in soil fertility, decomposition of organic material, bioremediation, nutrient cycling, ecological engineers, biocontrol, bioindicator, and plant growth. That is why earthworms are very most important for efficient agriculture (Blouin et al. 2013; Bertrand et al. 2015; Shi et al. 2020). Nowadays weed also becomes a major problem in agriculture land. The harvested weed can be used to form vermicompost. For examples; vermicomposting of water hyacinth (*Eichhornia crassipes*) improves the growth of crossandra (*Crossandra undulaefolia*), lady's finger (*Hibiscus esculentus*), brinjal (*Solanum melongena*), cluster bean (*Cyamopsis tetragonoloba*), chili (*Capsicum annuum*), and tomato (*Lycopersicon esculentum*). Thus, it is an approach towards sustainability because as VCM, weed volume is decreased and we also get organic fertilizer. Therefore, we can say earthworms by using VCM indirectly control the volume of weed (Gajalakshmi and Abbasi 2002).

Food demand is growing every day for the increasing population, and agriculture in the next decades will depend upon sustainable development to obtain abundant food from less agricultural land. For sustainable development, we cannot neglect the different important benefit of earthworms. The decline of earthworm directly or indirectly affects the sustainability of the environment. If earthworms are extinct from the earth, we cannot imagine sustainable development (Hobbs 2007).

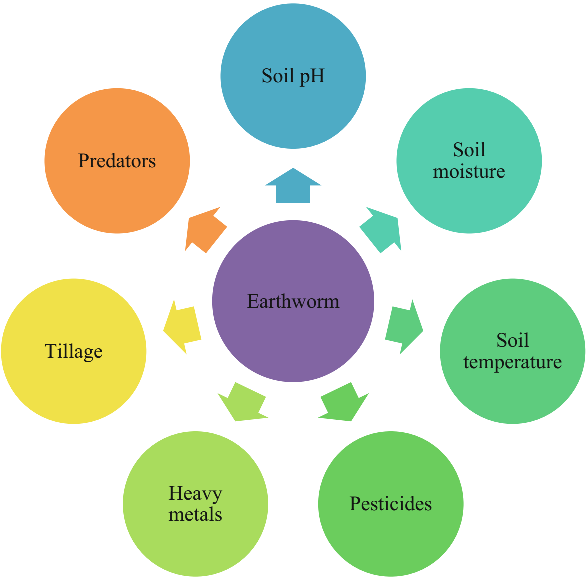
2.9 Factors Affecting Earthworm Population

Due to beneficial attributes of earthworms, they are vital for sustainable development but still, their performance of worked depends on several factors (Fig. 2.9). Earthworms are a susceptible organism, and their abundance richness and evenness were strongly related to the different environmental condition (Edwards and Bohlen 1996; McCallum et al. 2016).

2.9.1 Soil pH

Soil pH affects the bioavailability of nutrient, pesticides, and HMs in soil (Cheng and Wong 2002). Edwards and Bohlen (1996) observed that earthworms are difficult to see below the soil pH 4.3 (Mccallum et al. 2016). They are unusually found in soil pH more than 4.0–4.5 and usually absent in less than 3.5 soil pH (Räty and Huhta 2003; Chan et al. 2004). Most of the earthworm's species have optimum soil pH near to neutrality, i.e. pH =7.0. However, each earthworm species has different tolerance range to soil pH (Edwards and Bohlen 1996; Chan 2003). For example, *Allolobophora chlorotica* is an acid intolerant species and is found in a narrow range of pH 4.7 to 5.7 (Mccallum et al. 2016). Räty and Huhta (2003) observed that *A. caliginosa*, *L. terrestris*, and *L. rubellus* are found between soil pH 4 and 7. Earthworms grow and reproduce better in its optimum soil pH. For example, the survival and reproduction of *E. fetida* get reduced in acidic soil (Bernard et al. 2009).

Fig. 2.9 Factors affecting the earthworm population



2.9.2 Soil Moisture

The presence of soil moisture influences the earthworm activities, survival, growth, abundance, sexual maturation, reproductive success, and longevity (Edwards and Bohlen 1996; Berry and Jordan 2001; Ivask et al. 2006). For instance, most favorable moisture for *P. excavatus* is 80%. Nevertheless, juvenile and clitellate of this earthworm prefer 81% moisture content, whereas maximum cocoon deposition occurred at 78.5% moisture. Thus, it was concluded that moisture content affects the reproduction and growth of earthworms (Hallatt et al. 1992). The optimum moisture for *L. terrestris* and *Amynthas hupeiensis* is 30% (Berry and Jordan 2001; Richardson et al. 2009). Perreault and Whalen (2006) observed that *A. caliginosa* and *L. terrestris* have maximum surface casting at −5 kPa (kilo Pascal) than −11 kPa whereas maximum burrows length at -11 kPa than -5 kPa.

2.9.3 Soil Temperature

Soil temperature affects the earthworm survival rate, growth, and reproduction. Survivorship and growth have occurred at different soil temperature (Presley et al. 1996). The hatchling growth and cocoon development of *L. terrestris* occurred rapidly at 20 °C but the greatest annual production at 15 °C. So, we can say that maximum weight gain was noticed at the optimum temperature range 15–20 °C (Berry and Jordan 2001; Perreault and Whalen 2006). An almost similar effect was seen in *A. caliginosa* (Perreault and Whalen 2006). They developed better at optimum temperature, e.g. *E. eugeniae* optimum temperature for reproductive success at 22–25 °C, but it can survive up to 30 °C (Viljoen and Reinecke 1992; Richardson et al. 2009). *Aporrectodea caliginosa* and *L. rubellus* are also remained unaffected up to a wide range of soil temperature (Eggleton et al. 2009). Soil temperature and moisture together influence the earthworms, for example; in case of *E. fetida*, maximum survival occurred at moderate temperature, and moisture 20 °C and 3 ml (milliliter) g^{-1}, respectively, and this pattern remains up to ontogeny. Generally, survivorship more depends upon soil temperature than its moisture (Presley et al. 1996).

2.9.4 Pesticides

Pesticides directly affect earthworm actions, e.g. *E. andrei* significantly avoids the methomyl (1.36–23 mg kg^{-1}) contaminated soil (Pereira et al. 2009). *Eisenia fetida* lost 14.8–25.9% of their biomass in pure glyphosate (26.3 $mgkg^{-1}$) contaminated soil (Pochron et al. 2020). Gowri and Thangaraj (2019) observed that with increasing Monocrotophos (agrochemical pesticide) concentration, there was an increase of earthworms mortality, abnormal sperm count (necrospermia, oligospermia, and asthenospermia) and defective cocoons in *E. eugeniae* and *P. barotensis*, whereas

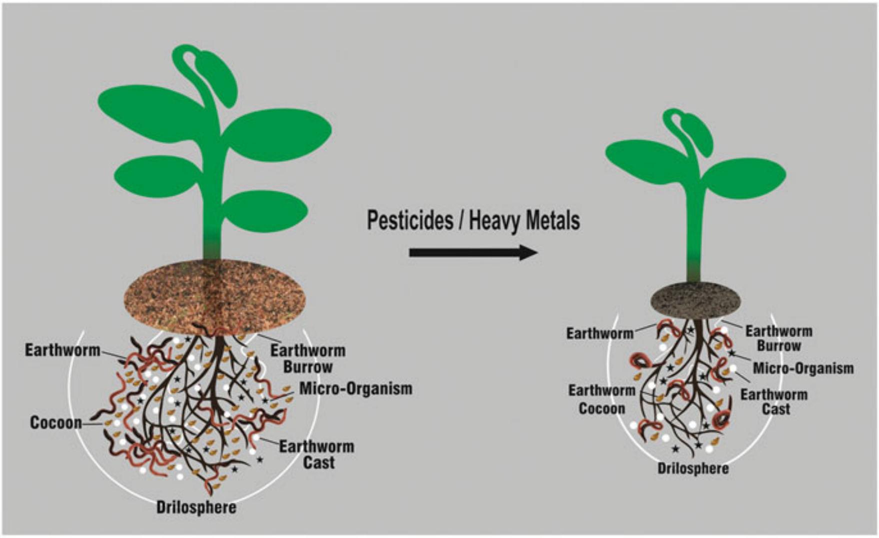


Fig. 2.10 Effect of pesticides and heavy metals on earthworms

microbial proliferation was decreased in *L. mauritti* as concentration was increased (Kavitha et al. 2020). Agrochemical pesticides cause major histopathological changes in the body wall, chloragogenous tissue, villi, longitudinal muscle, vacuolization, blood sinus, and necrosis in *E. eugeniae, P. barotensis*, and *L. mauritti.* Therefore, effects the growth, reproductive potential and survivability of these earthworms (Gowri and Thangaraj 2019; Yao et al. 2020; Kavitha et al. 2020). The DNA (deoxyribonucleic acid) is the genetic material of organisms, which is a vital component in cells. Pesticides damage the DNA, which is a very fatal condition for earthworms. This damage increases as concentration and period of exposure to pesticides were increased. For example, the DNA damage of *E. fetida* even at a dose of 0.1 mg kg^{-1} of Cyantraniliprole (Qiao et al. 2019) and Endosulfan at 0.5 mg kg^{-1} doses injured the ultrastructure of the nucleus (Shi et al. 2020). The pesticidal impact on earthworm is illustrated in Fig. 2.10.

2.9.5 Heavy Metals

Exposure time and dose-dependent effect of HMs were observed in earthworms (Zheng and Canyang 2009; Höckner et al. 2020). Heavy metals can accumulate in earthworm's tissue and cast. Therefore, these metals harm earthworms (Zhang et al. 2020). Comparatively, a higher concentration of HMs in the tissue of endogeic species (*M. posthuma*) was noticed than anecic species (*L. mauritii*) (Suthar et al. 2008). Heavy metals contaminated soil retards the growth, locomotory ability, sperm morphology, fertility rate and also causes the death of earthworm. Cocoon production is more sensitive to soil contamination than mortality of earthworm

(Žaltauskaitė and Sodienė 2010; Zheng and Canyang 2009). Zinc (39.9%) and Cd (84.1%) were noticed in *A. morrisi* cast, and these metals affect the earthworm growth (Zhang et al. 2020). This may be due to changes in the immune system of earthworms by Cd (Höckner et al. 2020). Poor survival of *A. chlorotica* in highly HMs contaminated Bukowno soil might be due to lack of adaptive immunity (Höckner et al. 2020) and/or maybe due to impairment of immune functions of earthworm (Homa et al. 2003). Wang et al. (2020) observed that *E. fetida* shows the dose-dependent effect with Nickel (Ni) concentration in growth rate, respiration and histological change in body wall, digestive and reproductive system. Analysis of mRNA expression showed that Cd affects the regeneration, glycolysis/glucogenesis pathways, biosynthesis of amino acids, and apoptosis of *E. fetida* (Fig. 2.10) (Chai et al. 2020).

2.9.6 Tillage

Earthworm burrows system is an important indicator to define its soil activity (Langmaack et al. 1999; Bertrand et al. 2015). A three-year experiment shows that conventional tillage causes reduction of 90% transmitting burrows (Chan 2004). Species richness, abundances, and biomass of earthworms are directly influenced by soil tillage (Emmerling 2001). However, *A. rosea* and *A. caliginosa* (endogeic species) are not much affected by soil tillage (Ivask et al. 2007).

2.9.7 Predators

Earthworms are used as food by different animals like Flatworm (Boag and Yeates 2001), beetles, ants, fishes, amphibians, reptiles, birds, and mammals (Muys and Granval 1997; Sazima 2007; Onrust et al. 2017). It has been reported that in Britain and Faroe, *Arthurdendyus triangulatus* (*Artioposthia triangulata*) flatworm affects the soil ecological system because of reducing lumbricidae earthworm populations. Some species of flatworm which act as a predator like *Bipalium kewense* survive at high temperatures and are only found in greenhouses while other species like *A. albidus* are obligate predators of earthworms. *A. australis, Australoplana sanguinea alba*, and *Caenoplana coerulea* also prey on earthworms. Tissue conversion from earthworms to the flatworm is 9.7% (Gibson et al. 1997; Boag and Yeates 2001).

Earthworm feeding by spiders is probably rare. Earthworm predation was in only eight araneomorphs and three mygalomorph families. In the wild, earthworms are generally eaten by larger (14–35 mm) spiders like *Ancylomedes rufus* but predation also is done by smaller (6–8 mm) spiders like *Amaurobius fenestralis* (Nyffeler et al. 2001; Ross 2008). *Platycryptus undatus* (Jumping spider) feeding on *Aporrectodea caliginosa* (Ross 2008).

Microscopic screening of gut contents of beetles showed the presence of earthworm cuticle and chaetae in their gut. Earthworm proteins are also reported in their gut (Nyffeler et al. 2001; Ingerson-Mahar 2002). Beetles eat earthworm as food because they improve fitness parameters, for example, Carabid beetle, *Pterostichus melanarius* (King et al. 2010).

In Amphibian, earthworms are secondary preferences as food, e.g. *Bufo bufo* (Macdonald 1983), *Xenorhina oxycephala* (Allison and Kraus 2000), and *Craugastor rhodopis* (Aguilar-López and Pineda 2013).

The legless lizard *Anguis fragilis* fecal samples showed that 86% of this lizard eats earthworms (Brown et al. 2012). Worm snake (*Carphophis vermis*), *T. ordinoides*, *Helicops angulatus* (brown-banded water snake), *Atractus, Diadophis, Geophis, Ninia, Virginia, Gomesophis*, and *Sordellina* also eat earthworms. Earthworms, respectively, form 3.4 and 30.8% stomach content of *T. sirtalis* and *T. ordinoides* (Grazziotin et al. 2012; Strüssmann et al. 2013).

Earthworms are reported in the diet of various birds like Mockingbird (*Mimus saturninus*), tawny owl (*Strix aluco*), wryneck (*Jynx torquilla*), song thrush (*Turdus musicus)* (Macdonald 1983), *oystercatchers* (*Haematopus ostralegus*), starling (*Sturnus vulgaris*), crows, gulls, wrens, and grackles (Muys and Granval 1997; Stephenson et al. 1997; Seamans et al. 2015; Sazima 2007). Earthworms form about 5.5, 2.4, and 0.3% contribution in the diet of *Falco tinnunculus* (kestrels), blackbird (*Turdus merula*) (Macdonald 1983), and starling (*Sturnus vulgaris*), respectively (Muys and Granval 1997; Onrust et al. 2017).

From the mammals, maximum records for predation on earthworm noticed in order Insectivora particularly by Soricidae (Silcox and Teaford 2002). *Myosorex varius* (Shrews), *Microtus agrestis* (vole) (Reinecke et al. 2000) also used earthworms in their diet. Earthworms contribute about 3.4 and 4.3% as a diet of *Sorex fumeus* and *S. cinereus* (Macdonald 1983). About 20% caloric contribution of the fox (*Vulpes vulpes*) was through consumption of earthworms. 77.1% of foxes were feeding at a place where a large number of earthworms were present (Muys and Granval 1997).

2.10 Conclusions

As the world population is increasing agricultural land is decreasing day by day. Food scarcity is becoming a major problem to the present period of the escalating global population. Due to this tremendous population agriculture land is decreasing. For the next decade, to generate more food from less agricultural land, we will be dependent on sustainable development, and earthworm can contribute a crucial role in this development as it is now playing a significant role in this. We already study vermicompost (VCM) has many beneficial roles for soil fertility and plant growth for sustainable development. That is why VCM also called organic gold. In short, we can say earthworms directly and/or indirectly play a vital role in the sustainability of the environment.

2.11 Future Perspectives

Modern agriculture practices produce high yield but also have trenchant amount of ill effects due to continuous input of chemicals fertilizers beyond a certain limit. Persistent chemical has effects on the public as well as environmental health along with its effects on soil health. Therefore, these practices become questionable. The current research highlights to overcome these problems by using earthworms in different ways. There is need to find some new techniques and sustainable way so that earthworms can be used efficiently to overcome these problems. A significant challenge for the future is also to identify a sustainable system to optimize the soil faunal diversity with biomass and their impacts on soil quality.

References

Adhikary S (2012) Vermicompost, the story of organic gold: a review. Agric Sci 3(7):905

Aguilar-López JL, Pineda E (2013) An exotic species of earthworm preyed by Craugastor rhodopis (Anura: Craugastoridae) in Mexico. Herpetol Notes 6:335–336

Allison A, Kraus F (2000) A new species of frog of the genus Xenorhina (Anura: Microhylidae) from the north coast ranges of Papua New Guinea. Herpetol Sep 1:285–294

Ansari AA, Ori L, Ramnarain YI (2020) An effective organic waste recycling through vermicompost technology for soil health restoration. In: Meena RS (ed) Soil health restoration and management. Springer, Singapore, pp 83–112

Arancon NQ, Edwards CA, Bierman P, Welch C, Metzger JD (2004) Influences of vermicomposts on field strawberries. Effects on growth and yields. Bioresour Technol 93(2):145–153

Araujo Y, Luizão FJ, Barros E (2004) Effect of earthworm addition on soil nitrogen availability, microbial biomass and litter decomposition in mesocosms. Biol Fertil Soils 39(3):146–152

Bajiya R, Lakhran H, Kumar S, Seema (2017) Biochar for enhancing agricultural sustainability under climate change. Int J Curr Microb Appl Sci 6(2):1876–1883

Barker KR (2003) Perspectives on plant and soil nematology. Annu Rev Phytopathol 41(1):1–25

Barrios E (2007) Soil biota, ecosystem services and land productivity. Ecol Econ 64(2):269–285

Bartlett MD, Briones MJ, Neilson R, Schmidt O, Spurgeon D, Creamer RE (2010) A critical review of current methods in earthworm ecology: from individuals to populations. Eur J Soil Biol 46 (2):67–73

Bernard MJ, Neatrour MA, McCay TS (2009) Influence of soil buffering capacity on earthworm growth, survival, and community composition in the Western Adirondacks and Central New York. Northeast Nat 6(2):269–285

Berry EC, Jordan D (2001) Temperature and soil moisture content effects on the growth of *Lumbricus terrestris* (Oligochaeta: Lumbricidae) under laboratory conditions. Soil Biol Biochem 33(1):133–136

Bertrand M, Barot S, Blouin M, Whalen J, de Oliveira T, Roger-Estrade J (2015) Earthworm services for cropping systems. Rev Agron Sustain Develop 35(2):553–567

Bhadauria T, Kumar P, Kumar R, Maikhuri RK, Rao KS, Saxena KG (2012) Earthworm populations in a traditional village landscape in central Himalaya, India. Appl Soil Ecol 53:83–93

Bhardwaj P, Sharma R (2016) New records of earthworms from sugar-belt of Haryana. Bioscan 11 (1):53–56

Blanchart E, Julka JM (1997) Influence of forest disturbance on earthworm (Oligochaeta) communities in the Western Ghats (South India). Soil Biol Biochem 29(3–4):303–306

Blouin M, Zuily-Fodil Y, Pham-Thi AT, Laffray D, Reversat G, Pando A, Tondoh J, Lavelle P (2005) Belowground organism activities affect plant aboveground phenotype, inducing plant tolerance to parasites. Ecol Lett 8(2):202–208

Blouin M, Lavelle P, Laffray D (2007) Drought stress in rice (*Oryza sativa* L.) is enhanced in the presence of the compacting earthworm Millsonia anomala. Environ Exp Bot 60(3):352–359

Blouin M, Hodson ME, Delgado EA, Baker G, Brussaard L, Butt KR, Dai J, Dendooven L, Pérès G, Tondoh JE, Cluzeau D (2013) A review of earthworm impact on soil function and ecosystem services. Eur J Soil Sci 64(2):161–182

Boag B, Yeates GW (2001) The potential impact of the New Zealand flatworm, a predator of earthworms, in western Europe. Ecol Appl 11(5):1276–1286

Bottinelli N, Jouquet P, Capowiez Y, Podwojewski P, Grimaldi M, Peng X (2015) Why is the influence of soil macrofauna on soil structure only considered by soil ecologists? Soil Tillage Res 146:118–124

Bouche MB (1977) Strategies lombriciennes. In: Lohm U, Persson T (eds) Soil organisms as components of ecosystems, vol 25. Ecological Bulletins, Swedish Natural Science Research Council, Stockholm, pp 122–132

Brown GG (1995) How do earthworms affect microfloral and faunal community diversity? Plant Soil 170(1):209–231

Brown GG, Edwards CA, Brussaard L (2004) How earthworms affect plant growth: burrowing into the mechanisms. Earthworm Ecol 2:13–49

Brown DS, Jarman SN, Symondson WO (2012) Pyrosequencing of prey DNA in reptile faeces: analysis of earthworm consumption by slow worms. Mol Ecol Resour 12(2):259–266

Brussaard L (1997) Biodiversity and ecosystem functioning in soil. Ambio 26:563–570

Canellas LP, Olivares FL, Okorokova-Façanha AL, Façanha AR (2002) Humic acids isolated from earthworm compost enhance root elongation, lateral root emergence, and plasma membrane H+-ATPase activity in maize roots. Plant Physiol 130(4):1951–1957

Canti MG (2003) Earthworm activity and archaeological stratigraphy: a review of products and processes. J Archaeol Sci 30(2):135–148

Carpenter D, Hodson ME, Eggleton P, Kirk C (2007) Earthworm induced mineral weathering: preliminary results. Eur J Soil Biol 43:S176–S183

Chai L, Yang Y, Yang H, Zhao Y, Wang H (2020) Transcriptome analysis of genes expressed in the earthworm Eisenia fetida in response to cadmium exposure. Chemosphere 240:124902

Chan KY (2003) Using earthworms to incorporate lime into subsoil to ameliorate acidity. Commun Soil Sci Plant Anal 34(7–8):985–997

Chan KY (2004) Impact of tillage practices and burrows of a native Australian anecic earthworm on soil hydrology. Appl Soil Ecol 27(1):89–96

Chan KY, Baker GH, Conyers MK, Scott B, Munro K (2004) Complementary ability of three European earthworms (Lumbricidae) to bury lime and increase pasture production in acidic soils of South-Eastern Australia. Appl Soil Ecol 26(3):257–271

Chandran MS, Sujatha S, Mohan M, Julka JM, Ramasamy EV (2012) Earthworm diversity at Nilgiri biosphere reserve, Western Ghats, India. Biodivers Conserv 21(13):3343–3353

Cheng J, Wong MH (2002) Effects of earthworms on Zn fractionation in soils. Biol Fertil Soils 36 (1):72–78

Clark B, York R, Bellamy Foster J (2009) Darwin’s worms and the skin of the earth: an introduction to Charles Darwin’s the formation of vegetable Mould, through the action of worms, with observations on their habits (selections). Organ Environ 22(3):338–350

Clements RO, Murray PJ, Sturdy RG (1991) The impact of 20 years’ absence of earthworms and three levels of N fertilizer on a grassland soil environment. Agric Ecosyst Environ 36 (1–2):75–85

Coleman FC, Williams SL (2002) Overexploiting marine ecosystem engineers: potential consequences for biodiversity. Trends Ecol Evol 17(1):40–44

Dahiya S, Kumar S, Kumar S, Khedwal RS, Harender D, Chaudhary C, Ankush A (2018) Management practices for improving water use efficiency of crops for boosting crop production.

In: Rao RK, Sharma PK, Raghuraman M, Singh JK (eds) Agricultural, allied sciences & biotechnology for sustainability of agriculture, nutrition & food security. Mahima Publications, Varanasi., ISBN: 978-81-926935-8-3, pp 115–121

Darwin C (1881) The formation of vegetable mould through the action of worms: with observations on their habits. John Murray, London

Dash MC, Saxena KG (2012) Earthworms in the Himalaya and Western Ghats region of India: a review. The Bioscan 7(1):1–8

Decaëns T, Jiménez JJ, Barros E, Chauvel A, Blanchart E, Fragoso C, Lavelle P (2004) Soil macrofaunal communities in permanent pastures derived from tropical forest or savanna. Agric Ecosyst Environ 103(2):301–312

Deepshikha V (2011) A contribution to the earthworm survey fauna of Doon valley in Uttarakhand, India with special reference to a search for vermicomposting species. Bioremed Biodivers Bioavail 5(1):81–86

Densilin DM, Srinivasan S, Manju P, Sudha S (2011) Effect of individual and combined application of biofertilizers, inorganic fertilizer and vermicompost on the biochemical constituents of chilli (Ns-1701). J Biofertil Biopestici 2(106):2

Dhiman N, Battish SK (2006) Earthworms from northern Indian states with *Ocnerodrilusoccidentalis,* Eisen, 1878, as a new report from Punjab. Zoo's Print Jl 21 (1):2135–2137

Dominguez J, Edwards CA, Subler S (1997) A comparison of vermicomposting and composting. Biocycle 38:57–59

Edwards CA (1998) The use of earthworms in the breakdown and management of organic wastes. In: Edwards CA (ed) Earthworm ecology. CRC Press, Boca Raton, pp 327–354

Edwards CA, Bohlen PJ (1992) The effects of toxic chemicals on earthworms. In: Ware GW (ed) Reviews of environmental contamination and toxicology. Springer, New York, pp 23–99

Edwards CA, Bohlen PJ (1996) Biology and ecology of earthworms. Springer Science & Business Media, Berlin

Edwards CA, Subler S, Chen SK, Bogomolov DM, Straalen NM, Krivolutsky DA (1996) Essential criteria for selecting bioindicator species, processes, or systems to assess the environmental impact of chemicals on soil ecosystems. Bioindicat Syst Soil Pollut 31:67–84

Edwards CA, Arancon NQ, Sherman RL (2010) Vermiculture technology: earthworms, organic wastes, and environmental management. CRC press, Boca Raton, p 601

Eggleton P, Inward K, Smith J, Jones DT, Sherlock E (2009) A six year study of earthworm (Lumbricidae) populations in pasture woodland in southern England shows their responses to soil temperature and soil moisture. Soil Biol Biochem 41(9):1857–1865

Ekperusi OA, Aigbodion FI (2015) Bioremediation of petroleum hydrocarbons from crude oil-contaminated soil with the earthworm: *Hyperiodrilus africanus*. Biotech 5(6):957–965

Emmerling C (2001) Response of earthworm communities to different types of soil tillage. Appl Soil Ecol 17(1):91–96

Fadaee R (2012) A review on earthworm *Eisenia fetida* and its applications. Ann Biol Res 3 (5):2500–2506

Feller C, Brown GG, Blanchart E, Deleporte P, Chernyanskii SS (2003) Charles Darwin, earthworms and the natural sciences: various lessons from past to future. Agric Ecosyst Environ 99(1–3):29–49

Fischer C, Roscher C, Jensen B, Eisenhauer N, Baade J, Attinger S, Scheu S, Weisser WW, Schumacher J, Hildebrandt A (2014) How do earthworms, soil texture and plant composition affect infiltration along an experimental plant diversity gradient in grassland? PLoS One 9(6): e98987

Fracchia L, Dohrmann AB, Martinotti MG, Tebbe CC (2006) Bacterial diversity in a finished compost and vermicompost: differences revealed by cultivation-independent analyses of PCR-amplified 16S rRNA genes. Appl Microbiol Biotechnol 71(6):942

Fragoso C, Kanyonyo J, Moreno A, Senapati BK, Blanchart E, Rodriguez C (1999a) A survey of tropical earthworms: Taxonomy, biogeography and environmental plasticity. In: Lavelle P, Brussaard L, Hendrix P (eds) Earthworm management in tropical agroecosystems. CABI Publishing, New York, pp 1–26

Fragoso C, Lavelle P, Blanchart E, Senapati BK, Jimenez JJ, Martínez MA, Decaëns T, Tondoh J (1999b) Earthworm communities of tropical agroecosystems: origin, structure and influence of management practices. In: Lavelle P, Brussaard L, Hendrix P (eds) Earthworm management in tropical agroecosystems. CABI Publishing, New York, pp 27–55

Furlong MA, Singleton DR, Coleman DC, Whitman WB (2002) Molecular and culture-based analyses of prokaryotic communities from an agricultural soil and the burrows and casts of the earthworm *Lumbricus rubellus*. Appl Environ Microbiol 68(3):1265–1279

Fusaro S, Gavinelli F, Lazzarini F, Paoletti MG (2018) Soil biological quality index based on earthworms (QBS-e). A new way to use earthworms as bioindicators in agroecosystems. Ecol Indic 93:1276–1292

Gajalakshmi S, Abbasi SA (2002) Effect of the application of water hyacinth compost/vermicompost on the growth and flowering of *Crossandra undulaefolia*, and on several vegetables. Bioresour Technol 85(2):197–199

Garg N, Julka JM (2016) Diversity and new records of earthworms (oligochaeta: Annelida) from Haryana, a constituent of trans Gangetic plains, India. Megadrilogica 21(10):205–209

Gates GE (1959) On some earthworms from Taiwan. Am Mus Novit 1941:1–19

Gibson PH, Cosens D, Buchanan K (1997) A chance field observation and pilor laboratory studies of predation of the New Zealand flatworm by the larvae and adults of carabid and staphylinid beetles. Ann Appl Biol 130(3):581–585

Goswami R, Mondal CK (2015) A study on earthworm population and diversity with special reference to physicochemical parameters in different habitats of South 24 Parganas district in West Bengal. Rec Zool Surv India 115(1):31–38

Gowri S, Thangaraj R (2019) Studies on the toxic effects of agrochemical pesticide (Monocrotophos) on physiological and reproductive behavior of indigenous and exotic earthworm species. Int J Environ Health Res 22:1–4

Grazziotin FG, Zaher H, Murphy RW, Scrocchi G, Benavides MA, Zhang YP, Bonatto SL (2012) Molecular phylogeny of the new world Dipsadidae (Serpentes: Colubroidea): a reappraisal. Cladistics 28(5):437–459

Gupta A, Kumar A (2018) Climate resilient agro-technologies for enhanced crop and water productivity under water deficit agro-ecologies. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 339–356

Gupta C, Prakash D (2020) Novel bioremediation methods in waste management: novel bioremediation methods. In: Khosrow-Pour M (ed) Waste management: concepts, methodologies, tools, and applications. IGI Global, Hershey, pp 1627–1643

Haimi J, Huhta V (1990) Effect of earthworms on decomposition processes in raw humus forest soil: a microcosm study. Biol Fertil Soils 10(3):178–183

Hallatt L, Viljoen SA, Reinecke AJ (1992) Moisture requirements in the life cycle of *Perionyx excavatus* (Oligochaeta). Soil Biol Biochem 24(12):1333–1340

Hansen S (1996) Effects of manure treatment and soil compaction on plant production of a dairy farm system converting to organic farming practice. Agric Ecosyst Environ 56(3):173–186

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agric Sci Cambridge 145(2):127

Höckner M, Piechnik CA, Fiechtner B, Weinberger B, Tomanek L (2020) Cadmium-related effects on cellular immunity comprises altered metabolism in earthworm coelomocytes. Int J Mol Sci 21(2):599

Homa J, Niklinska M, Plytycz B (2003) Effect of heavy metals on coelomocytes of the earthworm *Allolobophora chlorotica*: the 7th international symposium on earthworm ecology· Cardiff Wales 2002. Pedobiologia 47(5–6):640–645

Huang K, Xia H, Zhang Y, Li J, Cui G, Li F, Bai W, Jiang Y, Wu N (2020) Elimination of antibiotic resistance genes and human pathogenic bacteria by earthworms during vermicomposting of dewatered sludge by metagenomic analysis. Bioresour Technol 297:122451

Ingerson-Mahar J (2002) Relating diet and morphology in adult carabid beetles. In: Holland JM (ed) The agroecology of carabid beetles, pp 111–136

Ismail A (1997) Vermicology: the biology of earthworms. Orient Longman, Hyderabad

Ivask M, Kuu A, Truu M, Truu J (2006) The effect of soil type and soil moisture on earthworm communities. Agric Sci 17:7–11

Ivask M, Kuu A, Sizov E (2007) Abundance of earthworm species in Estonian arable soils. Eur J Soil Biol 43:S39–S42

Jakhar SR, Kumar S, Jangir CK, Meena RS (2017) The role of mycorrhizal relationship in sustainable manner towards plant growth and soil fertility. Indian J Agric Allied Sci 3(4):19–24

Jangir CK, Singh D, Kumar S (2016) Yield and economic response of biofertilizer and fertility levels on black gram (Vigna mungo L.). Progress Res Int J 11(Special-VIII):5252–5254

Jangir CK, Panghaal D, Kumar S, Meena RS, Prince (2017) Enriching soil carbon stock through mitigating soil erosion. In: Rao RK, Sharma PK, Raghuraman M, Singh JK (eds) Agricultural, Allied Sciences & Biotechnology for Sustainability of Agriculture, Nutrition & Food Security. Mahima Publications, Varanasi, pp 415–419. ISBN: 978-81-926935-8-3

Jangir CK, Kumar S, Meena RS (2019) Significance of soil organic matter to soil quality and evaluation of sustainability. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 357–381

Jégou D, Brunotte J, Rogasik H, Capowiez Y, Diestel H, Schrader S, Cluzeau D (2002) Impact of soil compaction on earthworm burrow systems using X-ray computed tomography: preliminary study. Eur J Soil Biol 38(3–4):329–336

Joshi N, Aga S (2009) Diversity and distribution of earthworms in a subtropical forest ecosystem in Uttarakhand, India. Tropic Nat History 9(1):21–25

Jouquet P, Podwojewski P, Bottinelli N, Mathieu J, Ricoy M, Orange D, Tran TD, Valentin C (2008) Above-ground earthworm casts affect water runoff and soil erosion in northern Vietnam. Catena 74(1):13–21

Jouquet EP, Bloquel E, Doan TT, Ricoy M, Orange D, Rumpel C, Duc TT (2011) Do compost and vermicompost improve macronutrient retention and plant growth in degraded tropical soils? Compost Sci Utilization 19(1):15–24

Julka JM (1993) Earthworm resources of India and their utilization in vermiculture. The Director, Zoological Survey of India (ed) Earthworm resources and vermiculture. Calcutta 51–56

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017a) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in indo-Gangetic Plains of India. J Curr Microb and Appl Scie 6(3):152–163

Kakraliya SK, Kumar N, Dahiya S, Kumar S, Yadav DD, Singh M (2017b) Effect of integrated nutrient management on growth dynamics and productivity trend of wheat (*Triticum aestivum* L.) under irrigated cropping system. J Plant Devel Sci 9(1):11–15

Kavitha V, Anandhan R, Alharbi NS, Kadaikunnan S, Khaled JM, Almanaa TN, Govindarajan M (2020) Impact of pesticide monocrotophos on microbial populations and histology of intestine in the Indian earthworm Lampito mauritii (Kinberg). Microb Pathog 139:103893

King RA, Vaughan IP, Bell JR, Bohan DA, Symondson WO (2010) Prey choice by carabid beetles feeding on an earthworm community analysed using species-and lineage-specific PCR primers. Mol Ecol 19(8):1721–1732

Kumar S, Meena RS, Lal R (2018) Role of legumes in soil carbon sequestration. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 109–138. https://doi.org/10.1007/978-981-13-0253-4_4

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, Singapore, pp 337–375. https://doi.org/10.1007/978-981-13-7264-3_10

Lakhran H, Kumar S, Bajiya R (2017) Crop diversification: an option for climate change resilience. Trends in Biosc 10(2):516–518

Langmaack M, Schrader S, Rapp-Bernhardt U, Kotzke KV (1999) Quantitative analysis of earthworm burrow systems with respect to biological soil-structure regeneration after soil compaction. Biol Fertility Soils 28(3):219–229

Lavelle P, Pashanasi B, Charpentier F, Gilot C, Rossi JP, Derouard L, André J, Ponge JF, Bernier N (1998) Large-scale effects of earthworms on soil organic matter and nutrient dynamics. St. Lucie Press, Boca Raton

Lavelle P, Decaëns T, Aubert M, Barot S, Blouin M, Bureau F, Margerie P, Mora P, Rossi JP (2006) Soil invertebrates and ecosystem services. Eur J Soil Biol 42:S3–S15

Le Bayon RC, Moreau S, Gascuel-Odoux C, Binet F (2002) Annual variations in earthworm surface-casting activity and soil transport by water runoff under a temperate maize agroecosytem. Geoderma 106(1–2):121–135

Lee KE (1985) Earthworms: their ecology and relationships with soils and land use. Academic Press Inc., Sydney

Li K, Li P, Li H (2010) Earthworms helping economy, improving ecology and protecting health. Int J Global Environ Issues 10(3–4):354–365

Liu M, Cao J, Wang C (2020) Bioremediation by earthworms on soil microbial diversity and partial nitrification processes in oxytetracycline-contaminated soil. Ecotoxicol Environ Saf 189:109996

Loehr RC, Martin JH, Neuhiauser EF, Malecki MR (1984) Waste management using earthworms: engineering and scientific relationships. NTIS, Springfield

Macdonald DW (1983) Predation on earthworms by terrestrial vertebrates. In: Satchell JE (ed) Earthworm ecology. Springer, Dordrecht, pp 393–414

McCallum HM, Wilson JD, Beaumont D, Sheldon R, O'Brien MG, Park KJ (2016) A role for liming as a conservation intervention? Earthworm abundance is associated with higher soil pH and foraging activity of a threatened shorebird in upland grasslands. Agric Ecosyst Environ 223:182–189

Meena RS, Kumar S, Pandey A (2017) Response of sulfur and lime levels on productivity, nutrient content and uptake of sesame under guava (*Psidium guajava* L.) based Agri-horti system in an acidic soil of eastern Uttar Pradesh, India. J Crop and Weed 13(2):222–227

Meena RS, Kumar V, Yadav GS, Mitran T (2018) Response and interaction of *Bradyrhizobium japonicum* and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Kumar S, Yadav GS (2019) Soil carbon sequestration in crop production. In: Meena RS (ed) Nutrient dynamics for sustainable crop production. Springer, Singapore, pp 1–39. https://doi.org/10.1007/978-981-13-8660-2_1

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depthand amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Meysman FJ, Middelburg JJ, Heip CH (2006) Bioturbation: a fresh look at Darwin's last idea. Trends Ecol Evol 21(12):688–695

Mohan VC, Watts P, Kaur A (2013) Diversity and distribution of earthworm species in Guru Nanak Dev University Campus, Amritsar, Punjab, India. Res J Agric Sci 1(2):35–40

Munnoli PM, Da Silva JA, Saroj B (2010) Dynamics of the soil-earthworm-plant relationship: a review. Dynamic Soil Dynamic Plant 4(1):1–21

Muys B, Granval PH (1997) Earthworms as bio-indicators of forest site quality. Soil Biol Biochem 29(3–4):323–328

Najar IA, Khan AB (2011) Earthworm communities of Kashmir valley, India. Trop Ecol 52 (2):151–162

Ngo PT, Rumpel C, Dignac MF, Billou D, Duc TT, Jouquet P (2011) Transformation of buffalo manure by composting or vermicomposting to rehabilitate degraded tropical soils. Ecol Eng 37 (2):269–276

Nyffeler M, Moor H, Foelix RF (2001) Spiders feeding on earthworms. J Arachnol 29(1):119–125

Onrust J, Loonstra AJ, Schmaltz LE, Verkuil YI, Hooijmeijer JC, Piersma T (2017) Detection of earthworm prey by ruff *Philomachus pugnax*. Ibis 159(3):647–656

Paliwal R, Julka JM (2005) Checklist of earthworms of western Himalaya, India. Zoos' Print J 20 (9):1972–1976

Pereira JL, Antunes SC, Castro BB, Marques CR, Gonçalves AM, Gonçalves F, Pereira R (2009) Toxicity evaluation of three pesticides on non-target aquatic and soil organisms: commercial formulation versus active ingredient. Ecotoxicology 18(4):455–463

Pérès G, Vandenbulcke F, Guernion M, Hedde M, Beguiristain T, Douay F, Houot S, Piron D, Richard A, Bispo A, Grand C (2011) Earthworm indicators as tools for soil monitoring, characterization and risk assessment. An example from the national bioindicator programme (France). Pedobiologia 54:S77–S87

Perreault JM, Whalen JK (2006) Earthworm burrowing in laboratory microcosms as influenced by soil temperature and moisture. Pedobiologia 50(5):397–403

Pochron S, Simon L, Mirza A, Littleton A, Sahebzada F, Yudell M (2020) Glyphosate but not Roundup® harms earthworms (*Eisenia fetida*). Chemosphere 241:125017

Pop VV (1998) Earthworm biology and ecology – a case study: the genus Octodrilusomodeo, 1956 (Oligochaeta, Lumbricidae), from the Carpathians. In: Edwards CA (ed) Earthworm ecology. St. Lucie Press, Boca Raton, pp 65–100

Prakash O (2017) Biodiversity of earthworms and their distribution in different regions of Uttar Pradesh state of India. IOSR J Pharm 7:01–09

Presley ML, McElroy TC, Diehl WJ (1996) Soil moisture and temperature interact to affect growth, survivorship, fecundity, and fitness in the earthworm *Eisenia fetida*. Comp Biochem Physiol A Physiol 114(4):319–326

Qiao Z, Zhang F, Yao X, Yu H, Sun S, Li X, Zhang J, Jiang X (2019) Growth, DNA damage and biochemical toxicity of cyantraniliprole in earthworms (*Eisenia fetida*). Chemosphere 236:124328

Rabatin SC, Stinner BR (1988) Indirect effects of interactions between VAM fungi and soil-inhabiting invertebrates on plant processes. Agric Ecosyst Environ 24(1–3):135–146

Rajkhowa DJ, Bhattacharyya PN, Sarma AK, Mahanta K (2015) Diversity and distribution of earthworms in different soil habitats of Assam, north-East India, an indo-Burma biodiversity hotspot. Proc Natl Acad Sci India Sect B Biol Sci 85(2):389–396

Räty M, Huhta V (2003) Earthworms and pH affect communities of nematodes and enchytraeids in forest soil. Biol Fertil Soils 38(1):52–58

Ravindran B, Wong JW, Selvam A, Sekaran G (2016) Influence of microbial diversity and plant growth hormones in compost and vermicompost from fermented tannery waste. Bioresource Technol 217:200–204

Reinecke AJ, Reinecke SA, Musilbono DE, Chapman A (2000) The transfer of lead (Pb) from earthworms to shrews (*Myosorex varius*). Arch Environ Contam Toxicol 39(3):392–397

Richardson DR, Snyder BA, Hendrix PF (2009) Soil moisture and temperature: tolerances and optima for a non-native earthworm species, *Amynthas agrestis* (Oligochaeta: Opisthopora: Megascolecidae). Southeast Nat 8(2):325–335

Ross LK (2008) A jumping spider feeding on an earthworm. Peckhamia 71(1):1–2

Sanchez-Hernandez JC, Ro KS, Díaz FJ (2019) Biochar and earthworms working in tandem: research opportunities for soil bioremediation. Sci Total Environ 688:574–583

Sathianarayanan A, Khan AB (2006) Diversity, distribution and abundance of earthworms in Pondicherry region. Trop Ecol 47(1):139–144

Sazima I (2007) Like an earthworm: chalk-browed mockingbird (*Mimus saturninus*) kills and eats a juvenile watersnake. Revista Brasileira de Ornitologia 19(3):450–452

Scott-Fordsmand JJ, Weeks JM (2000) Biomarkers in earthworms. In: Ware GW (ed) Reviews of environmental contamination and toxicology. Springer, New York, NY, pp 117–159

Seamans TW, Blackwell BF, Bernhardt GE, Potter DA (2015) Assessing chemical control of earthworms at airports. Wildl Soc Bull 39(2):434–442

Sharma RK, Poonam B (2014) Earthworm diversity in trans-gangetic habitats of Haryana, India. Res J Agric Forestry Sci 2(2):2320–6063

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019) Growth, yield and quality of cluster bean (*Cyamopsis tetragonoloba*) as influenced by integrated nutrient management under alley cropping system. Indian J Agric Sci 89(11):1876–1880

Shi Y, Shi Y, Zheng L (2020) Individual and cellular responses of earthworms (*Eisenia fetida*) to endosulfan at environmentally related concentrations. Environ Toxicol Pharmacol 74:103299

Shih HT, Chang HW, Chen JH (1999) A review of the earthworms (Annelida: Oligochaeta) from Taiwan. Zool Stud 38(4):435–442

Shuster W, McDonald L, McCartney D, Parmelee R, Studer N, Stinner B (2002) Nitrogen source and earthworm abundance affected runoff volume and nutrient loss in a tilled-corn agroecosystem. Biol Fertil Soils 35(5):320–327

Silcox MT, Teaford MF (2002) The diet of worms: an analysis of mole dental microwear. J Mammal 83(3):804–814

Singer AC, Jury W, Luepromchai E, Yahng CS, Crowley DE (2001) Contribution of earthworms to PCB bioremediation. Soil Biol Biochem 33(6):765–776

Sinha RK, Agarwal S, Chauhan K, Chandran V, Soni BK (2010) Vermiculture technology: reviving the dreams of sir Charles Darwin for scientific use of earthworms in sustainable development programs. Technol Invest 1(03):155

Sinkakarimi MH, Solgi E, Colagar AH (2020a) Interspecific differences in toxicological response and subcellular partitioning of cadmium and lead in three earthworm species. Chemosphere 238:124595

Sinkakarimi MH, Solgi E, Colagar AH (2020b) Subcellular partitioning of cadmium and lead in *Eisenia fetida* and their effects to sperm count, morphology and apoptosis. Ecotoxicol Environ Saf 187:109827

Stephens PM, Davoren CW (1997) Influence of the earthworms *Aporrectodea trapezoides* and *A. rosea* on the disease severity of *Rhizoctonia solani* on subterranean clover and ryegrass. Soil Biol Biochem 29(3–4):511–516

Stephenson GL, Wren CD, Middelraad IC, Warner JE (1997) Exposure of the earthworm, *Lumbricus terrestris*, to diazinon, and the relative risk to passerine birds. Soil Biol Biochem 29(3–4):717–720

Strüssmann C, de Brito ES, Marques OA (2013) What do water snakes eat? First report of predation by a Neotropical Hydropsini snake on giant earthworms (Glossoscolecidae). Salamandra 49 (1):48–50

Sun Y, Zhao L, Li X, Xu H, Weng L, Yang L, Li Y (2020) Response of soil bacterial and fungal community structure succession to earthworm addition for bioremediation of metolachlor. Ecotoxicol Environ Saf 189:109926

Suthar S (2009) Earthworm communities a bioindicator of arable land management practices: a case study in semiarid region of India. Ecol Indic 9(3):588–594

Suthar S (2011) Earthworm biodiversity in western arid and semiarid lands of India. Environmentalist 31(1):74–86

Suthar S, Singh S, Dhawan S (2008) Earthworms as bioindicator of metals (Zn, Fe, Mn, Cu, Pb and Cd) in soils: is metal bioaccumulation affected by their ecological category? Ecol Eng 32 (2):99–107

Tognetti C, Laos F, Mazzarino MJ, Hernandez MT (2005) Composting vs. vermicomposting: a comparison of end product quality. Compost Sci Utilization 13(1):6–13

Tondoh JE, Monin LM, Tiho S, Csuzdi C (2007) Can earthworms be used as bio-indicators of land-use perturbations in semi-deciduous forest? Biol Fertil Soils 43(5):585–592

Tripathi G, Bhardwaj P (2004) Earthworm diversity and habitat preferences in arid regions of Rajasthan. Zoo's Print Journal 19(7):1515–1519

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan Region, India. Int J Chem Studies 5 (4):1558–1560

Verma D, Bharti S (2010) Earthworm resources in the Gangetic plain of Uttar Pradesh, India. Int J Biodivers Conserv 2(6):134–139

Viljoen SA, Reinecke AJ (1992) The temperature requirements of the epigeic earthworm species *Eudrilus eugeniae* (Oligochaeta)—a laboratory study. Soil Biol Biochem 24(12):1345–1350

Vivas A, Moreno B, Garcia-Rodriguez S, Benítez E (2009) Assessing the impact of composting and vermicomposting on bacterial community size and structure, and microbial functional diversity of an olive-mill waste. Bioresour Technol 100(3):1319–1326

Wang G, Xia X, Yang J, Tariq M, Zhao J, Zhang M, Huang K, Lin K, Zhang W (2020) Exploring the bioavailability of nickel in a soil system: physiological and histopathological toxicity study to the earthworms (*Eisenia fetida*). J Hazard Mater 383:121169

Wissuwa J, Salamon JA, Frank T (2012) Effects of habitat age and plant species on predatory mites (Acari, Mesostigmata) in grassy arable fallows in eastern Austria. Soil Biol Biochem 50:96–107

Wollny E (1890) Untersuchungenüber die beeinflussung der ackerkrumedurch die thätigkeit der regenwurmer. Forschungen Geb AgriculturPhysik 13:381–395

Wu P, Wang C (2019) Differences in spatiotemporal dynamics between soil macrofauna and mesofauna communities in forest ecosystems: the significance for soil fauna diversity monitoring. Geoderma 337:266–272

Yao X, Zhang F, Qiao Z, Yu H, Sun S, Li X, Zhang J, Jiang X (2020) Toxicity of thifluzamide in earthworm (*Eisenia fetida*). Ecotoxicol Environ Saf 188:109880

Žaltauskaitė J, Sodienė I (2010) Effects of total cadmium and lead concentrations in soil on the growth, reproduction and survival of earthworm *Eisenia fetida*. Ekologija 56(1–2):10–16

Zhang C, Dai J, Chen X, Li H, Lavelle P (2020) Effects of a native earthworm species (*Amynthas morrisi*) and *Eisenia fetida* on metal fractions in a multi-metal polluted soil from South China. Acta Oecol 102:103503

Zheng R, Canyang LI (2009) Effect of lead on survival, locomotion and sperm morphology of Asian earthworm, *Pheretima guillelmi*. J Environ Sci 21(5):691–695

Bio-pesticides for Agriculture and Environment Sustainability

3

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Abstract

Crop losses caused by various pathogens, i.e., bacteria, fungi, insects, weeds, etc., reduce agricultural productivity and cause economic loss to the country. Usage of chemical fertilizers, pesticides, and other aids had a significant role as a protagonist during the green revolution. It favored the scenarios of agricultural production, and all seemed to rely on these aids in a very smooth manner. The negative side of these chemically synthesized fertilizers and pesticides got the limelight when the chemical residues started to accumulate in the soil, water, and products. Their impact on the environment became visible when these started to contaminate and deteriorate the quality of soil, water, and other vegetation. Thus, chemicals used in these pesticides have direct as well as indirect implications on human health and environment. Global demand is for safe, non-toxic, nutritious food products. These products can be obtained only by good agricultural practices, followed by safe post-harvest processing techniques. Sustainable agricultural practices cannot be achieved only by scientific expertise. Farmers' field knowledge for combating problems related to pests should also be given proper importance. More requirement of organic and pesticide independent food ingredients is the prime driving force for innovative ideas formulating safer pesticides for agriculture practices. The stakeholders are now concentrating on alternatives to these chemically synthesized pesticides in the form of bio-pesticides, which is a marvelous innovation in the field of agriculture science. Bio-pesticides formulated with microbes or plant extracts promote the growth of beneficial micro-organisms and control the targeted harmful pests. Pyrethrin, neem extracts, essential oils, and alkaloids extracted from various plants show significant effects on pests which include repellency, feeding deterrence, negative impact on oviposition, growth inhibition, disruption during mating, chemo-sterilization, etc. Application of bio-pesticides and natural biodegradable nano-pesticides is the key to success in chemical-free agricultural practices in future.

Keywords

Agriculture · Bio-pesticides · Crop protection · Environment · Sustainability · Efficacy · Nano-pesticides · Plant diseases

Abbreviations

%	Per cent
IPM	Integrated pest management
TMV	Tobacco mosaic virus
USEPA	United State Environmental Protection Agency
WHO	World Health Organization

3.1 Introduction

The exploding population of the world has currently crossed the mark of 7.7 billion and is still growing at a flying scale (Roser et al. 2020; Kumar et al. 2017b). Therefore, this has created a need for an increase in the production so as to meet the food requirement for all. According to the United Nation Prospectus (2011), the world population will rise and get to 10.12 billion in the last era of the century, if the same trends continue (Meena et al. 2016, 2017). The actual state questions the current rate of agricultural production. It demands superior, progressive, and more productive agricultural resources to meet up the future requisites. The innovators and beneficiaries have devoted a significant fraction of their time and energy to meet up these demands looking for the solutions to surfeit the production as well as to perk up the quality of the produce. Before the Green Revolution, production figures were not as satisfying as there was not enough food production to satisfy needs of every individual at all levels (Meena et al. 2018a). The Green Revolution is biggest of the initial milestones in the field of agricultural science as the agricultural production over the map marked an exponential growth. The success of the same was because of the novel methods, techniques, and agricultural aids which were introduced.

The lack of nutritional contents, pesticide attacks, weeds, and other plants fostering the nutritional bout had a decisive role determining the agricultural produce and still tend to do so. The introduction of chemical pesticides and other insecticides helped the farmers and cultivators to cut the damage done by these external agents. These chemically originated insecticides and pesticides were successfully regulating control over the damage. The fertilizers were helpful to plants in meeting their nutritional requisites. The pesticides which include insecticides, rodenticides, herbicides, fungicides, and many others were crucial resolving the rampage as these kept the insects and other microbes competing for plants and animals in control so that their presence does not affect the yield. Moreover, because of the same, the agricultural produce marked a booming production (Oerke 2006).

As time passed, the undetected effects of chemically synthesized pesticides came to the sight, which was flabbergasting. It was hard to believe, but these chemically synthesized insecticides and pesticides were deteriorating the condition of the environment. The chemicals which played a crucial role in controlling the damage done to the crops were themselves damaging and deteriorating the quality of soil and environment (Meena et al. 2018b, 2020b). The chemicals present in these pesticides started to affect the fertility index of the soil as their concentrations in the soil increased with the time (Pimentel 2005). As the chemicals present were able to interact with the soil particles and their retention and interaction with soil particles depended on the interactions taking place in between the chemical modules and soil particles. Not only the soil, but these chemical pesticides were additionally imposing their detrimental consequences on the water cycle (Kole et al. 2001). The chemicals interfered with the life processes of the micro-organisms at the initial levels which played as a stepping stone to the annihilation scenario of the reservoir. The issues seemed to have no solution as the use of the chemical pesticides had become an indispensable part of agricultural practices, and without their use, there was no option till a time available as efficient as these chemically synthesized pesticides because the primitive techniques of pest-control were not that effective in controlling the damage that lowered the produce.

The hard work and dedication of the innovators and scientists all over the globe paved the way by introducing bio-pesticides in the scenario. The bio-pesticides are the pest management tools which were introduced with the sole motive of control on insects and pests without harming the environment, which includes the soil as well as the water profile of the native place. The environment has direct and indirect implications on human and other life-forms residing and inhabiting the place or for the ones who are consuming the produce that is obtained via usage of chemically originated pesticides (Wani and Lee 1995). Bio-pesticides after a bunch of scientific explorations came in light as the substitutes for the chemically synthesized pesticides. Bio-pesticides are synthesized with the help of microbes, plant extracts, and other biologically active principles. Bio-pesticides are one of the gifts of the innovators and biotechnology, and articulated configurations of key constituents rely on micro-organisms like virus, bacteria, fungi or few naturally occurring and industrially prepared substances like plant extracts, semiochemicals, and secondary metabolites. Besides all this, bio-pesticides include organisms which terminate the agricultural pests. There are various types of bio-pesticides based on the constituents that regulate various but specific properties and can be framed in numerous products (Knowles 2006).

Bio-pesticides are principally classified into three broad categories on the ground of critical methods viz., (1) bio-chemical (insect sex hormones), (2) phyto-inserted protectants (botanical pesticides like neem oil, rotenone, tobacco suspension, etc.), and (3) plant assisted pesticide-agrocin extracted from *Metarhizium anisopliae* and Trichoderma (USEPA 2008). The usage of bio-pesticides on the field is gaining recognition with time as the farmers, and the cultivators are now well aware of the negative impacts associated with the usage of chemically originated pesticides. The cultivators are now switching to bio-pesticides as they understand what is better for them as well as for the consumers. Consumers are now demanding for safe, organic, herbal, and plant-based products. The chapter deals with advantages and limitations of bio-pesticides over chemical pesticides for agriculture as well as the environment.

3.2 Hazards of Chemical Pesticides

The chemically originated pesticides which came in trend with the onset of the green revolution had a bunch lot of benefits which provoked the agriculturalists to use them over the primitive techniques of pest management. The directions of usage were also straightforward and time-saving, which created a feeling of reliance in their fields. The farmers wanted to get the best of their time and energy that inspired them using these pesticides. These chemical pesticides include variety of products for different requirements whether it is insecticides, herbicides, fungicides, rodenticides, or any other product which helps them to check over these crop-annihilating species (Fig. 3.1). Numerous other benefits of these besides

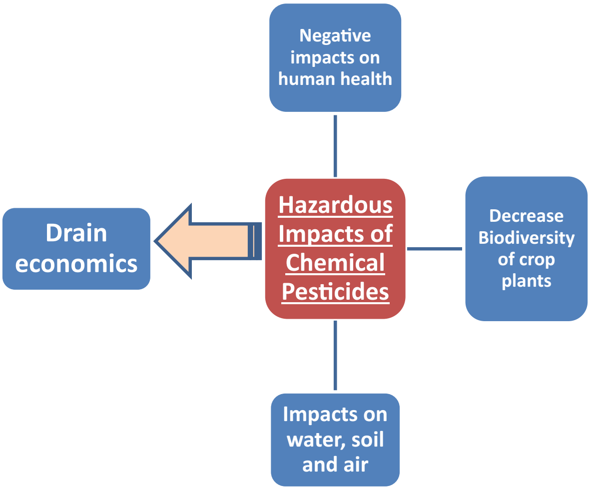

Fig. 3.1 Hazards of chemical pesticides

improving the net productivity were the superior quality of food produce and cost-effectiveness.

1. Negative impacts on human health: Pesticides exposure can affect fertility and reproduction, diabetes, obesity, degenerative diseases, e.g., Parkinsonism, cancer, asthma, depression, and anxiety.
2. Decreasing biodiversity of crop plants: Pesticides have been linked with loss of many plants, animals, and microbial species.
3. Impacts on water, soil, and air: Run-off contaminates surface, groundwater. Soil micro-organisms, as well as the earthworms, are poisoned affecting soil fertility and drift vitalizations contaminate air, rain, fog, and snow.
4. Drains economics: As a whole, all the negative impacts cause a drain in the economics of a country.

Despite of several benefits, hazardous or the adverse effects of the same cannot be neglected at all. Srivastava et al. (2011) examined pesticide residues' contaminants exist in assorted consolidations in the 20 medico herbs often bargained for commercial market medicinal herbs commonly sold from Lucknow. These chemically originated pesticides also have deteriorating effects on the environment like their use on fields had led to severe health implications on men, animals, and other beneficial living organisms. These consequences and their sub-consequences were hazardous. It became necessary for the researchers to come up with the concept of bio-pesticides to avoid these consequences, which are elucidated. World Health Organization (WHO) uses the Acute Toxicity Hazard Categories from Globally Harmonized System of Classification and Labelling (GHS) at the starting point for classification. The WHO has given a classification of toxicity for various products based on LD_{50} (lethal dose) value for the rats (Table 3.1).

Table 3.1 WHO classification of toxicity level based on lethal doses (WHO 2005)

WHO class	Toxicity	LD50 for the rat (mg g^{-1} body weight)	
		Oral application	Dermal application
Ia	Extremely hazardous	<5	<50
Ib	Highly hazardous	5–50	50–200
II	Moderately hazardous	50–2000	200–2000
III	Slightly hazardous	Over 2000	Over 2000
U	Unlikely to present acute hazard	5000 or higher	5000 or higher

mg g^{-1} – milligram per gram

3.2.1 Soil Contamination

The effect of these pesticidal chemicals and transformation products on soil depends on the extent of interaction in them and the soil particles. The levels of contamination depend on the degree of retention which is proportional to the interactions which take place in between the soil and the chemical modules; this degrades the fertility index of the soil with the time. It depends on their retention, water-solubility, and other physical parameters. The presence of the chemicals and their transformation products lead to deterioration in the quality of the soil. Soil micro-flora is also mainly got affected due to these accumulating pesticides and their residues. Geno-toxic effects on earthworm mortality in soil due to pesticides' residues were evaluated by Bustos-Obregn and Goicochea (2002). Various researches showed pesticidal accumulation in soil and their negative impacts (Mishra et al. 2012; Yu et al. 2013; Chiaia-Hernandez et al. 2017; Hvězdová et al. 2018). Many efforts to remediate and regulate pesticide contamination from soils are being carried out (Flaherty et al. 2013; Su et al. 2014; Chen et al. 2015; Morillo and Villaverde 2017).

3.2.2 Air and Non-Subject Vegetation Contamination

Pesticidal sprays can target and hit the non-target vegetation directly or indirectly. The drifting of these chemically originated pesticides can increase depending on the usage. The drifting range of the pesticides could be anything in between few yards to several miles. Soil, air, water, and vegetation of different regions were evaluated for the presence of toxic pesticides (Fang et al. 2017; Moore et al. 2017; Stillway et al. 2019). There have been several cases of species getting to the verge of being endangered as they are being affected by the drifting of the pesticides. The United States Fish and Wildlife Service has recognized that almost 74 threatened species which are threatened by glyphosate itself (USEPA 1986), which is a pesticidal chemical constituent.

3.2.3 Surface Water Contamination

The pesticides′ chemicals can purview the surface water through run-off from the treated plants and soil. The phenomenon of surface water contamination is pervasive. More than 90% of the water samples contain at least one or more pesticidal chemicals (Kole et al. 2001). The chemicals which did not penetrate within the soil also had an antagonistic role as they run off the levels and reached the nearby water bodies. The increased concentrations of these chemically synthesized pesticides in the water reservoir made the water incompatible for daily-life usage for humans as well as made difficult for the life which existed in the reservoir to survive as the ecological homeostasis was disturbed (Kumar et al. 2017a). The phenomenon of bio-magnification of the chemical pesticides which takes place at different levels of the life existing in the body is critical to understand. These chemicals have an influence and impact the functioning of the biological processes of the water body as well as of the living individuals existing in the body. In a recent study, identification and quantification of 34 compounds from pesticides of three different categories, i.e., herbicides, fungicides, and insecticides, in the Louros River located at Epirus region, North-Western Greece was done (Kapsi et al. 2019).

3.2.4 Groundwater Contamination

The chemicals, which were able to penetrate the soil layers, reach the groundwater and contaminated the same. The quality index of the groundwater was affected severely as the concentrations of these pesticides increased with the time as there was no compromise made with their usage on the field. The contamination of groundwater is a problem which is prevalent all over the globe. In agricultural areas where pesticides are more frequently used, as about 95% of the population relies upon groundwater (Singh et al. 2018).

3.2.5 Implications on Human Health

Pesticide exposure to farmers and the public is causing various health hazards. Farmers get exposed to a pesticide known as occupational toxicity. Significant levels of pesticide exposure caused burning eyes (64.2%) and blurred vision (54.7%) among apple farmers of studied areas (Bagheri et al. 2018). The suicidal exposure to chemical pesticides being used in agriculture is another relevant issue. In this review, we are discussing environmental problems related to pesticide effects on the environment. The chemicals from the pesticides had severe health implications on humans. There is an impressive number of chemicals in these chemically originated pesticides which impose potential risk on humans as well as on the other life-forms and unwanted side effects on the environment. Pesticide affects neuron function at the molecular level by distrusting microtubules and hyper-phosphorylation, which lead to Alzheimer diseases (Zaganas et al. 2013). Extensive use of different type of chemicals affects the whole population of the area; there is no segment of the population which is safeguarded from the exposure of chemical pesticides and fertilizers. There are reports of pesticides exhibiting their severe effects on humans causing Parkinson's disease posing neuro-toxic effects (Ritz et al. 2016), hormone disruption, reproductive anomalies (Sifakis et al. 2017), lowering intelligence, and even leading to cancer in some cases. The association of exposure to different classes of pesticides, including insecticides, herbicides, and fungicides with the incidence of cancers has been highlighted during the past half-century (Mostafalou and Abdollahi 2017). Ewence et al. (2015) review the results of a study whereby toxicity data relating to human health effects of 98 pesticides were assessed for endocrine disruption potential.

3.3 Bio-pesticides: Concept and Advancements

The concept of bio-pesticides was introduced to lower the hazardous impacts of the chemo-synthesized pesticides on the surroundings. Bio-pesticides seemed like to be a much reliable and efficient source of controlling the damage that is done or made to the yield by pests. The bio-pesticides include micro-organisms or the extracts from such organisms or plants which only inflict the damage or harm-causing pests. Furthermore, majorly they do not leave any adverse and side effects on the plant body and the environment. Bio-pesticides can be considered as the best possible substitutes of the chemically originated pesticides because they are highly efficient, target-specific and also, they do not tend to impose any annihilating or deteriorating impact on the environment. Bio-pesticides on account of their configuration and mechanisms are distinguished from the chemical pesticides. The structure is different as bio-pesticides are obtained from nature, adding a touch of biotechnology to it, and the difference in functioning is way too different. Based on the active ingredient which is present, bio-pesticides are grouped as (USEPA 2008): microbial bio-pesticides and botanical bio-pesticides.

3.3.1 Microbial Bio-pesticides

Microbial bio-pesticides include numerous kinds of pathogens, for instance, tiny organisms like fungi, bacteria, and viruses and organisms which are treated top act as an agent of pest-control. Microbial bio-pesticides are formerly known as biocontrol agents. Microbial pesticides have way high range of pros and no points to add affecting and causing toxicity in the environment favoring its usage (MacGregor 2006). There are more than 3000 species of biocontrol agents, which include various bacteria, fungi, and viruses which are responsible for causing diseases in pests and other harmful organisms. The microbial bio-pesticides have several constraints also in spite of great potential like lethal response in other organisms (Jindal et al. 2013).

Table 3.2 Microbial biocontrol agents (present in bio-pesticides) of various plant pathogens

Bio-agent against pathogens	Crop	Pathogen
Trichoderma viride, *T. harzianum*	Cowpea (*Vigna unguiculata*)	*Macrophomina phaseolina*
Pseudomonas fluorescens (F113)	–	*Pythium* spp.
Bacillus cereus	–	*Phytophthora medicaginis*
Trichoderma viride	Pigeon pea (*Cajanus cajan*)	*Fusarium udum*
T. viride, *T. virens*	Ginger (*Zingiber officinale*)	*Pythium*, *Rhizoctonia solani*
T. Harzianum	Cardamom (*Elettaria cardamomum*)	*Phytophthora*
T. Koningii	Wheat (*Triticum aestivum*)	*Ustilago segetum* var. *tritici*
Trichoderma spp.	Mulberry (*Morus alba*)	*Cercospora moricola*
T. viride, *T. harzianum*	Rose (*Rosa* spp.)	*Botrytis cinereal*

Pathogenic micro-organisms are used as active ingredient of the microbial pesticides against species other than their hosts, like *Bacillus thuringiensis* which can be used as a pathogen for killing a different variety of pests (Kumar et al. 2016; Meena et al. 2020a). Microbial bio-pesticides can also be used in combination with the chemically originated pesticides as residues of these formulations may have less impact on the surroundings and human health. Moreover, the reason which favors its usage in the field is that these promote and favor the growth of beneficial micro-organisms as their degenerates or residues mainly act as manures as they are generated from biotic components. The major problem or challenge that is faced in the usage of microbial bio-pesticides is that because of its narrow specificity; it is used with conventional synthetic pesticides. This combination is used in inappropriate proportions to inhibit or kill the living organisms. The most commonly used microbial bio-pesticides are controlling pests and other crop-damaging organisms, such as bio-fungicides like *Trichoderma* and, *Pseudomonas* control the growth of fungal pathogens, bioherbicides containing *Phytophthora* spp. control the growth of weeds, and bio-insecticides containing *Bacillus thuringiensis, Pseudomonas* spp., etc. are harmful to insect or make the crop unsuitable for digesting. Table 3.2 is depicting some of the pathogens controlled by biocontrol agents of the microbial world.

3.3.2 Botanical Bio-pesticides

Botanical bio-pesticides are obtained from any plant part or the whole plant body, which can neutralize or kill the harmful pests and/or control of the weeds. The applications of plant-based bio-pesticides for protection against insect pests and other damage-causing forms have become a part of new and innovative agriculture practices as well as traditional agriculture practices including organic farming. Identification of over 6000 species of botanical species has been made that has the insect-killing potential as well as is being used as an insecticide. A great variety of these has been derived from plants such as neem (*Azadirachta indica*), tobacco (*Nicotiana tabacum*), and pyrethrum, which are used as a safer pesticide. Environment-friendly characteristics of botanical pesticides are their lubricious property and little surrounding prospects as compared to the chemically synthesized pesticides. Pesticides derived from plants show minimal residual activity and affect a minimum number of non-target species of insects. Botanical bio-pesticides show compatibility with integrated pest management (IPM) programs (Xu et al. 2011). Issues with the commercialization of the botanical bio-pesticides are quality control and standardization processes which make its usage on the field a more unlikely. Botanical bio-pesticides like traditional synthetic pesticides can lead to pest resistance if used in improper and excessive quantities. The phytotoxicity is also a matter of concern with some botanical bio-pesticides (Stevenson et al. 2012).

3.4 Production and Bioavailability of Bio-Pesticides

The production of bio-pesticides is dependent mainly on the active ingredient which is used in its formulations. The active ingredient is the deciding parameter which plays crucial aspects in the bio-pesticides composition. The bio-pesticides which are mainly of three types grouped on rely of the active ingredient, namely (1) microbial bio-pesticides, (2) botanical bio-pesticides, and (3) semiochemicals. The active ingredient which is different in each of them governs the formulation technique for the same. Like, in the case of microbial bio-pesticides, the active ingredient is the micro-organism which is useful in controlling the damage that is made to the crops by the pests and insects. So, the formulation here involves using these micro-organisms in such a way to use it for the purpose. The micro-organisms are biogenetically treated in such a manner that their action spectrum is reduced in such a manner in which the application is concerned. Viability of bioactive microbes depends on their shelf life in the formulation selected (Table 3.3). Regarding their physical state, bio-pesticide formulations can be divided into liquid and dry (talc,

Table 3.3 Viability of different formulation containing micro-organisms after 30 days of storage, population ($\times 10^8$ CFU ml^{-1})* (Sources: Bhat et al. 2009; Salaheddin et al. 2010; Kumar et al. 2013)

Biocontrol agent	Talc powder	Charcoal based
Bacillus subtilis s 49	27.5	4.2–7.9
Pseudomonas fluorescens s 32	40.1	–
Pseudomonas fluorescens s 93	33.7	–
Trichoderma viride	20.2	18.3
Trichoderma harzianum	3.2	–

**CFU* colony formation units

powder and charcoal-based) formulations. Furthermore, these formulations are divided into sub-formulation based on the method of applications, i.e., dust particles, seed-dressing formulations, water-dispersible granules, suspensions, and many others. Similarly, in case of botanical bio-pesticides, the active ingredients are the derivatives of the plant parts or the whole plant body which are formulated in such a way that their usage on the field is efficient and commercially viable. The formulation techniques are highly specific and complex as they sometimes require changes to be made at bio-molecular levels with knowledge of biotechnology and high precision.

Microbial pesticides contain separate active ingredients, which are specific for its target pests (Kawalekar 2013). Non-target beneficial pests are therefore safe by these pesticides, and ecological balance is maintained. The growth rate of usage of bio-pesticides per annum is approximately 10% (Bailey and Mupondwa 2006). In India, this rate was around 5% until 2014. However, in previous years, increasing pest resistance to synthetic pesticides and rising awareness towards using safe and non-toxic substances in agriculture, this rate is increasing. American countries use a higher amount of bio-pesticides (45%) followed by the European Union (20%) and rest by other countries (Bailey et al. 2010). Neem-based pesticides, *Bacillus thuringiensis*, nuclear polyhedrosis viruses, and *Trichoderma* are the dominant microbial bio-pesticides produced and used in India (Mazid et al. 2011). Bacterial pesticides have a wide range of shelf life from a few days to several months, according to the preparation and retention of the micro-organisms (Table 3.3).

Similar ways of the composition of bio-pesticide formulations are available being used for synthetic pesticides in general. Formulations must be suitable to be used in the same sprayers or equipment being available to the local farmers to reduce the cost.

3.5 Bio-pesticides in Crop Protection

All over the world, 67,000 pest species have been estimated that damage field crops (Ross and Lembi 1985). Fungal and bacterial diseases are challenging to cure, so the primary concern is to control and prevent their growth to prevent the damage to the yield. In the case of countries like India, where a large number of crop varieties are grown to fit into the different agro-climatic conditions, the widely divergent cultural practices in vogue compound problems of controlling plant diseases. The losses caused to the crop as well as to the individual plants may be categorized as direct or indirect losses. Direct losses consist of primary and secondary losses. Primary yield losses are mainly affecting yield, quality, price of control, surplus cost of harvesting, surplus cost of grading, costs of replacements, and loss of income by less profitable replacement crop. Secondary losses are due to spoilage of sowing and planting material, soil-borne diseases, weakening by premature defoliation of trees/perennials, cost of control of unexpected diseases, etc. Indirect losses are mainly related to farm, rural community, exporters, wholesale and retail trade, consumers, legislation, environmental problems, etc.

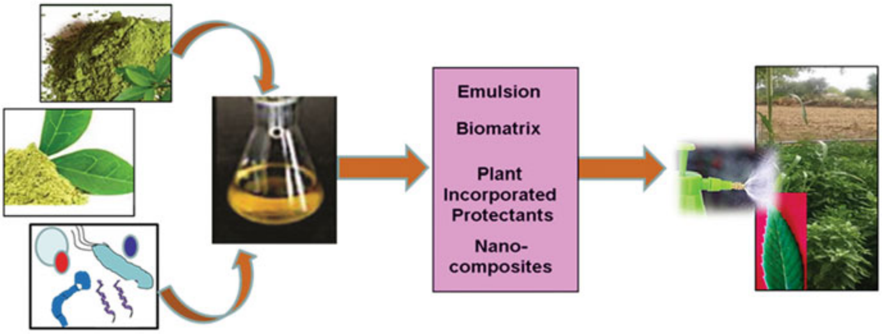

Fig. 3.2 Herbal and microbial pesticides after formulation showcasing non-toxic and safe applications in field

In a country like India, it can be said that almost every economically cultivated crop is infected by at least one disease (Rangaswami and Mahadevan 2012). Adverse effects which these disease-causing micro-organisms like fungi and bacteria impose on the products include a decrease in production, galls, over-growths, wilts, root rots, leaf spots, blights, cankers, specks, and many more. However, the more recent trends in agriculture and biotechnology have given rise to newer problems in plant pathology. The damage caused by pathogenic micro-organisms is one of the crucial reasons for food scarcity in some countries because a handsome lot of agricultural produce gets damaged.

Bio-pesticides may be a good alternative for chemical methods of crop protection if more practical and economical. Formulations containing latent/living cells, bioactive compounds have shown the ability to harbor plant disease resistance against diverse micro-organisms. The judicial use of bio-pesticides at the right stage and in the right quantity can protect crop plants and attribute in increasing final crop amount of yield. Soil contains a large quantity of insoluble nutrients. Microbial pesticides can transform insoluble nutrients into a soluble form and make them available for crop plants. *Bacillus* has shown diversity in their mode of action. They facilitate colonization of the ecologically beneficial organism in rhizosphere. They have been successfully used in bio-control products effective on *Colletotrichum gloeosporioides*, *Cercospora* spot on Avocado in South Africa (Cawoy et al. 2011). Figure 3.2 reveals that herbal and microbial pesticides after formulations showcase non-toxic and safe applications in the field.

Plant extracts showing biocidal property are screened for efficacy in the laboratory. If efficacy is found to be significant, the formulation is designed. If toxicity is negligible, registration can be granted. Regnault-Roger et al. (2005) mentioned two generations of botanical pesticides: first in which crude extracts like neem extract, nicotine, rotenone, rhynia, pyrethrum, and essential oils are included, and the second generation consists of synthetic pyrethroids and azadirachtin and other new potential botanicals. Phytochemicals with biotechnological advances to formulate can work as superior pesticides over already available pesticides. The era of synthetic and advanced plant products shows more efficacies over products being used traditionally globally. Besides enormous medicinal properties of neem, it is traditionally known in the world for its pesticidal activity of plant residues, seed oil, seed extract, leaf extract, leaf powder, and oil.

3.5.1 Application on Viral Diseases

Viruses cause significant loss to most of the crop plants. Viral diseases in many vegetable crops causing rusts and wilts, late blight, and ring rot of potato extensively occur in India. These are transmitted through various insects and other vectors. Sunflower necrosis virus disease causes significant damage to the production of sunflower (*Helianthus annuus* L.) in India (Sardaru et al. 2014). Two plant growth-promoting microbial consortia consisting of different strains of *Bacillus licheniformis*, *Pseudomonas aeruginosa*, and *Streptomyces fradiae* were used to control sunflower necrosis virus (Srinivasan and Mathivanan 2009). Powder and liquid formulations of the above plant growth-promoting micro-organisms were evaluated along with control in farmers' fields. Bitter gourd plants treated with *Bougainvillea spectabilis* inoculated with bitter gourd yellow mosaic virus (whitefly transmitted geminivirus) reduced the disease incidence, and increased the plant growth (Rajinimala et al. 2009). Integrated management of viral diseases and vectors in tomato (*Solanum lycopersicum*) and chilli (*Capsicum annuum*) through nanomaterial encapsulated with phytochemicals can be a better option to reduce the viral diseases.

Flavonoids reduce the tobacco mosaic virus (TMV) concentration mainly due to the defensive role in some of virus-infected plants. Flavones isolated from *Cassia siamea*, *Garcinia bracteata*, and *Hypericum chinense*; some of these compounds showed an inhibition rate of TMV (Luvisi et al. 2017).

3.5.2 Application on Bacterial Diseases

The bacterial diseases are majorly caused by the members of the genera: *Erwinia*, *Pectobacterium*, *Xanthomonas*, *Spiroplasma*, Phytoplasma, and many others. The Green Revolution in cereal crop production has generated confidence in the minds of the public regarding meeting the future food requisites of the booming population. There are several devastating diseases such as a bacterial blast (*Pyricularia oryzae*) of rice (*Oryza sativa*), which is extensively observed in tropical Asia, where approximately 60% of the world population lives (UNDES Affairs 2011). Chitosan (poly-D-glucosamine) is recently being incorporated in bio-pesticides. Bacteria are hypersensitive to the chitosan and its derivatives; it could be expected that chitosan may protect the plant from bacterial diseases (Hassan and Chang 2017). Chitosan exhibited antimicrobial activity against both Gram-positive and Gram-negative bacteria like *Staphylococcus aureus* and *Escherichia coli,* respectively; these were incorporated in biodegradable hollow nano-capsules (Pinheiroa et al. 2015).

Caesalpinia coriaria (divi-divi) is a potential candidate plant that could be successfully exploited for the management of the diseases caused by different pathogenic strains of *Xanthomonas* spp. (Mohana and Raveesha 2006).

3.5.3 Application on Fungal Diseases

There are approximately 8000 species of fungi known to cause most of the diseases on crop plants. Talking in detail, most of the fungal pathogenic conditions are created mainly two groups of fungus viz., (1) fungus from phylum Ascomycota and (2) phylum Basidiomycota. The members of Ascomycota cause black spots on roses, *Fusarium* wilt, canker rot, black rot and anthracnose in mangoes (*Mangifera indica*), papaya (*Carica papaya*), and other plants. The members of Basidiomycota cause brown patches, soybean (*Glycine max*) rust, and Ganoderma butt rot in palms. A range of fungal causative agents like *Fusarium moniliforme*, *Rhizoctonia solani*, *Macrophomina phaseolina*, *Colletotrichum*, *Pythium*, *Phytophthora*, *Alternaria,* etc. have been successfully controlled by *Trichoderma harzianum* and *T. viride* (Elad et al. 1983; Kefialew and Ayalew 2008; Sangeetha et al. 2011; Sriram et al. 2010; Svetlana et al. 2010; Harleen and Chander 2011; Mathew et al. 2011; Kalita et al. 2012).

Nimbidin (supposedly a conglomeration of several tri-terpenoids from neem seed oil) has shown fungicidal activity against a wide range of fungi viz., *Rhizoctonia solani, Aspergillus tenuis, Fusarium oxysporum, Helminthosporium nodulosum,* and *Curvularia tuberculata*.

3.5.4 Application on Disease Caused by Nematodes and Mites

Nematodes and mites are important microscopic pests of field crops, posing a significant threat to their yield. This loss is projected at approximately 12.3% (157 billion dollars) globally (Singh et al. 2015). Out of which, 40.3 million dollars have been reported from India (Singh et al. 2015). Other economically important 20 crops suffer a 14% yield loss globally (Prakash et al. 2014). Average yield loss due to nematodes is 12.3% (Gaur and Pankaj 2009).

Recently, Cao et al. (2015) reported strain Bs-1 of *Bacillus subtilis* showed strong nematicidal effects and caused egg hatching inhibition and repellence of *Meloidogyne incognita*. Mites from a different group of phytophagous organisms cause wounds/injuries to different plant tissues. These injuries are entry points for indirect penetration for many bacteria, viruses, and fungi. Mites feed on plant parts, lay their eggs, and this stimulates growth hormones in plants. Growth hormones induce hyperplasia and hypertrophy, resulting in galls on affected plant parts. Hence, mites not only cause abnormal growths but also reduce plant vigor and transmit some dangerous viruses, fungi, bacteria, and diseases (Sarwar 2015).

3.5.5 Application on Diseases Induced by Insects

Insect group of pests are a significant threat to forest trees as well as a vector for many cereal and vegetable crops. These pests have been widely controlled by broad-spectrum chemical pesticides and physical strategies under IPM. Spore forming bacteria comprise one or more proteins which exhibit toxic effect to a target organism. It is effective against target pests only to show limited or no effect on the non-target population. Cry toxin has been reported to control insect species related to Coleoptera, Lepidoptera, and Diptera. New combinations or diversity in protein can cover new ranges of insect pests. Recently, *Bacillus subtilis* BY2 has been reported to control *Sclerotinia sclerotiorum* on oilseed rape (*Brassica napus*) (Hu et al. 2019). Many viruses have been reported showing insecticidal activity in insects. Viruses belonging to the family *Baculoviridae* have been reported to show great potential to control various insects, and have been registered as insect control products globally (Erlandson 2008).

Nicotine has shown pesticidal effects against insect pests like aphids, thrips, and caterpillar (Casanova et al. 2002). Pyrethrum is known to control aphids, spider mites, leafhoppers, bugs, beetles, etc. (Glynne-Jones 2001). Rotenone extracted from tropical legumes functions to inhibit respiration of the cell. It also acts as a stomach poison and disrupts the cellular metabolism in insects (Fields et al. 1991). However high selectivity, *Azadirachta indica* derivatives affect approximately 400–500 species of insect's rapports to Coleoptera, Diptera, Dermaptera, Heteroptera, Calcifers, Homoptera, Hymenoptera, Isoptera, Lepidoptera, Thysanoptera, and several species of mites (Koul 2004). Neem products with various microbial preparations reported being effective against many pests. Neem extract with nuclear polyhedrosis viruses showed a lethal effect on gipsy moth instead of application of neem extract alone (Shapiro et al. 1994).

Musco doralbus, an entomopathogenic fungus has been used in fields, greenhouses, and warehouses as a bio-pesticide against certain insects (Moscardi 1999). *Aspergillus flavus* shows efficiency against *Aedes fluviatilis* and *Culex quinquefasciatus*, Conidia, mycelium, etc. sporulates in the host, and produces toxins. *Beauveria bassiana* and neem in combination applied against *Bemisia tabaci* (white fly) on eggplant (*Solanum melongena*) (Nicholson 2007). This application yielded good results against egg and nymph population. Synergistic effects can also be beneficial. Chitinase (insect moulting enzyme) splits chitin to smaller molecules is one of the potential bio-pesticides. Kramer and Mutukrishnan (1997) claimed that transgenic plants, chitinase, constitutively found to exhibit host plant resistance.

3.6 Bio-pesticides and Environment

3.6.1 Efficacy and Limitations in Application

Microbial pesticides mainly pose three types of challenges to pests: (a) competition for food, habitat, and survival, (b) creation of physical barriers, and (c) suppression by metabolites and chemicals. These ecological, physical, and biochemical mode of actions play a crucial role in the choice of manufacturing methods and the final cost of production (Hubbard et al. 2014). *B. subtilis* is an endospore-forming Gram-positive bacterium. These spores are heat, chemical, radiation resistant and provide long shelf life to pesticidal products made up by them. This gives *B. subtilis* commercial upper hand to other pesticides in the industry. The property of the bacterium poses ecological pressure on many bacterial and fungal pests' population for food and habitat. Secreted toxic metabolites are antimicrobial and inhibit the growth of other microbial population present in soil and nutrient-limited niche (Jack et al. 1995).

Alkaloids from various plants cause poisoning in pests. They camouflage the mode of action of organophosphates and carbamate insecticides (Regnault-Roger and Philogène 2008). Alkaloids like "nicotine" were used primarily but soon discovered to be nerve toxin to human as well. Pyrethrin is another widely used phytochemical showing the excellent biocidal property. Pyrethrin I and II esters cause hyperactivity and convulsions in most flying insects. Pyrethrin blocks sodium/potassium channels of nerve axons. The function is similar to dichloro diphenyl trichloroethane (DDT), the popular chemical pesticide. This activity of pyrethrin causes problems related to half-lives in ultraviolet radiation. Synthetic pyrethroids solved the problem with similar efficacy and negligible side effects on the environment. Pyrethroids with piperonyl butoxide work synergistically and paralyze insects for a shorter period (Rattan 2010).

Neem and its derivative allele-chemicals show a range of ramifications on pests which include repellency, feeding, negative impact on oviposition, growth inhibition, disruption during mating, chemo-sterilization, etc. (Schmutterer 1995). Its high level of efficiency and different mode of action largely reduce the risk of pest resistance. Few specific metabolites like azadirachtin (tri-terpenoid) demonstrate the anti-feeding activity to insects. This approach is non-toxic and gained popularity due to environment-friendly. Copping and Menn (2000) reported hormonal balance disruption in insects due to azadirachtin.

Essential oils extracted from neem, mint (*Mentha*), lavender (*Lavandula*), *Eucalyptus,* etc. inhibit acetylcholinesterase enzyme in insects (Keane and Ryan 1999). Bioactivity and bio-efficacy of essential oils depend upon type and nature of individual constituents, the process of extraction of oil.

Helicoverpa armigera is one of the most crucial pests of old-world cotton (*Gossypium* spp.) throughout Asia, Europe, Africa, and Australia. Xu et al. (2014) reported a novel densovirus (HaDNV-1); this increases the risk of that negatively impacting the efficiency of bio-pesticides currently being used (HaNPV and Bt toxin).

The results of this study showed essential implications for the selection of bio-pesticides and the need for more profound research into microbial interactions.

3.6.2 Dilemma of Nano-pesticides

Silver nano-particles capping from fungal bio-molecules from *Trichoderma harzianum* provide stable inhibitory activity on *Sclerotinia sclerotiorum* (Guilger-Casagrande et al. 2019). Similarly, in the last decade thousands of processes of nano-particles green synthesis and their application on viral, bacterial (Sondi 2004), fungal, and insect diseases have been reported (Servin et al. 2015; Pascoli et al. 2019). Metal nano-particles are proved to be toxic in some reports. Crude extracts from various plants contain different secondary metabolites. Bio-pesticides are considered purely safe while metal nano-materials are not considered to be ecofriendly. There is a dilemma in agriculture stakeholders to use these products or not. Nano-technology in recent times has emerged as an opportunity to develop pesticides which are more effective and pose the least threat to environmental. Pesticide formulations prepared using nano- and micro-emulsions have been reported as valuable tools as carriers of natural compounds with potential as bio-pesticides (Xu et al. 2010; Kalaitzaki et al. 2015; De Almeida et al. 2015). The innovative methods using micro- and nano-emulsions as carriers in pesticides' formulations decrease the use of organic solvent and increase the wettability, disparity, and penetration properties and improve the biological efficacy of pesticides (Koul et al. 2008; Kah et al. 2013; Kalaitzaki et al. 2015), mainly associated with a defensive role. The ecofriendly synthesis of nanoparticles using plant crude extracts and purified metabolites is novel substrates for large-scale production (Kuppusamy et al. 2016).

3.7 Conclusions

Innovative methods and bio-pesticides applications in agriculture may bring beneficial changes and sustainable stability in crop plants. Application of bio-pesticides in agriculture may reduce the bio-magnifications level in successive trophic levels of the ecology. Their uses minimize the usages of chemical pesticides, therefore may drastically reduce the barren land ratio of agricultural land. Bio-pesticides may help in increasing the efficiency of water update or water holding capacity of soil. The use of bio-pesticides and natural nano-pesticides will be the prime tool in chemical-free agricultural practices in India in the near future.

3.8 Future Perspectives

Indian agriculture is facing many challenges like diseases, climate change, soil quality degradation, loss of biodiversity, etc. (Deutsch et al. 2018). To increase the yield in a limited area of the field, farmers are trying all sorts of strategies. One of the strategies greatly benefitted rural area farmers was the use of chemical pesticides for crop against pests like an insect, nematodes, mites, fungi, bacteria, viruses, etc. Proper programs for the training of farmers for specific usage, quantity measurement, and time of usage of pesticides were not provided, resulted in an unorganized agriculture sector. Intensified and targeted research is required in the field to combat crop diseases, without negatively impacting yield and enhanced nutrition. Customers' awareness in the nutritional content, as well as pesticide pesticide-free propagation of food products, has compelled farmers and researchers to redesign agricultural practices. The increasing growth rate of nutraceuticals' market per annum and rising demand for organic food products is an alert to adopt agronomically compatible practices in agriculture. Application of bio-pesticides and natural biodegradable nano-pesticides is the key to success in chemical-free agricultural practices. We have to discover and formulate new active principles of bio-control having longer shelf life, easy to handle, and higher efficacy products which are environmentally safe. Commercialization of non-hazardous bio-pesticides is another concern of the manufacturing companies. Most of the companies are new and trying to sustain in the market. The government should give subsidy and aid to the companies for market survival. Increasing resistance in pests due to the application of chemical pesticides has driven awareness towards natural practices. Botanical extracts are being exploited because they tend to depend on various closely related active constituents rather than a single active ingredient. There are many key drivers to increase the growing market of bio-pesticides in near future that are growing organic food market demand for residue-free crop produce, and smooth registration than chemical pesticides.

References

Bagheri A, Emami N, Allahyari MS, Damalas CA (2018) Pesticide handling practices, health risks, and determinants of safety behavior among Iranian apple farmers. Hum Ecol Risk Assess 24 (8):2209–2223. https://doi.org/10.1080/10807039.2018.1443265

Bailey KL, Mupondwa EK (2006) Developing microbial weed control products: commercialization, biological, and technological considerations. In: Singh HP, Batish DR, Kohli RK, Binghamton NY (eds) Handbook of sustainable weed management. The Haworth Press, Binghamton, NY, pp 431–473

Bailey KL, Boyetchko SM, Längle T (2010) Social and economic drivers shaping the future of biological control: a Canadian perspective on the factors affecting the development and use of microbial bio-pesticides. Biol Control 52:221–229

Bhat KA, Anwar A, Lone GM, Hussain K, Nazir G (2009) Shelf life of liquid fermented product of *Trichoderma harzianum* in Talc. J Mycol Pl Pathol 39(2):263–265

Bustos-Obregn E, Goicochea RI (2002) Pesticide soil contamination mainly affects earthworm male reproductive parameters. Asian J Androl 4:195–199

Cao Y, Baoya T, Xinglai J, Shenghua S, Chaojun L, Keqin Z (2015) Associated bacteria of different life stages of *Meloidogyne incognita* using pyrosequencing-based analysis. J Basic Microbiol 55 (8):950–960

Casanova H, Carlos O, Carlos P, Alejandra V, María EM, Miguel A (2002) Insecticide formulations based on nicotine oleate stabilized by sodium caseinate. J Agric Food Chem 50(22):6389–6394. https://doi.org/10.1021/jf0257244

Cawoy H, Bettiol W, Fickers P, Ongena M (2011) Bacillus-based biological control of plant diseases. In: Stoytcheva M, Rijeka C (eds) Pesticides in the modern world – pesticides use and management. In Tech, pp 274–302

Chen M, Xu P, Zeng G, Yang C, Huang D, Zhang J (2015) Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: applications, microbes and future research needs. J Biotech Adv 33(6):745–755. https://doi.org/10.1016/j.biotechadv.2015.05.003

Chiaia-Hernandez AC, Keller A, Wächter D, Steinlin C, Camenzuli L, Hollender J, Krauss M (2017) Long-term persistence of pesticides and TPs in archived agricultural soil samples and comparison with pesticide application. Environ Sci Technol 51(18):10642–10651. https://doi.org/10.1021/acs.est.7b02529

Copping LG, Menn JJ (2000) Bio-pesticides: a review of their action, applications and efficacy. Pest Manag Sci 56:651–676

De Almeida VR, Giongo JL, Bolzan LP, Côrrea MS, Fausto VP, Dos Santos Alves CF, Lopes LQS, Boligon AA, Athayde ML, Moreira AP, Brandelli A, Raffin RP, Santos RCV, Brandelli A (2015) Antimicrobial activity of nanostructured Amazonian oils against *Paenibacillus* species and their toxicity on larvae and adult worker bees. J Asia Pac Entomol 18:205–210

Deutsch CA, Tewksbury JJ, Tigchelaar M, Battisti DS, Scott C (2018) Increase in crop losses to insect pests in warming climate. Science 361(6405):916–919

Elad Y, Chet I, Boyle P, Henis Y (1983) Parasitism of *Trichoderma* spp. on *Rhizoctonia solani* and *Sclerotium rolfsii* scanning electron microscopy and fluorescence microscopy. Phytopathology 73:85–88

Erlandson M (2008) Insect pest control by viruses. Encycl Virol 3:125–133. https://doi.org/10.1016/B978-012374410-4.00432-5

Ewence A, Brescia S, Johnson I, Rumsby PC (2015) An approach to the identification and regulation of endocrine disrupting pesticides. Food Chem Toxicol 78:214–220. https://doi.org/10.1016/j.fct.2015.01.011

Fang Y, Nie Z, Die Q, Tian Y, Liu F, He J, Huang Q (2017) Organo-chlorine pesticides in soil, air, and vegetation at and around a contaminated site in southwestern China: concentration, transmission, and risk evaluation. Chemosphere 178:340–349. https://doi.org/10.1016/j.chemosphere.2017.02.151

Fields PG, Arnason JT, Philogene BJ, Aucoin RR, Morand P, Soucy-Breau C (1991) Phototoxins as insecticides and natural plant defences. Mem Entomol Soc Can 9:29–38

Flaherty RJ, Nshime B, DeLaMarre M, DeJong S, Scott P, Lantz AW (2013) Cyclodextrins as complexation and extraction agents for pesticides from contaminated soil. Chemosphere 91 (7):912–920. https://doi.org/10.1016/j.chemosphere.2013.02.005

Gaur HS, Pankaj (2009) Nematodes: handbook of agriculture. ICAR Publications, New Delhi

Glynne-Jones A (2001) Pyrethrum. Pestic Outl 12:195–198

Guilger-Casagrande M, Germano-Costa T, Pasquoto-Stigliani T, Leonardo F (2019) Biosynthesis of silver nanoparticles employing *Trichoderma harzianum* with enzymatic stimulation for the control of *Sclerotinia sclerotiorum*. Sci Rep 9(1):43–51. https://doi.org/10.1038/s41598-019-50871-0

Harleen K, Chander M (2011) In vitro and in vivo evaluation of antagonistic potentiality of *Trichoderma* spp. against *Fusarium moniliforme* Sheld causing stalk rot of maize. Plant Dis Res 26(2):173–173

Hassan O, Chang T (2017) Chitosan for eco-friendly control of plant disease. Asian J Plant Pathol 11:53–70

Hu X, Roberts DP, Xie L, Qin L, Li Y, Liao X, Han P, Yu C, Liao X (2019) Seed treatment containing *Bacillus subtilis* BY-2 in combination with other *Bacillus* isolates for control of *Sclerotinia sclerotiorum* on oilseed rape. Biol Control 133:50–57

Hubbard M, Hynes RK, Erlandson M, Bailey KL (2014) The biochemistry behind bio-pesticide efficacy. Sustain Chem Process 2:18. https://doi.org/10.1186/s40508-014-0018-x

Hvězdová M, Kosubová P, Košíková M, Scherr KE, Šimek Z, Brodský L, Šudoma M, Škulcová L, Sáňka M, Svobodová M, Krkošková L, Vašíčková J, Neuwirthová N, Bielská L, Hofman J (2018) Currently and recently used pesticides in Central European arable soils. Sci Total Environ 613–614:361–370. https://doi.org/10.1016/j.scitotenv.2017.09.049

Jack RW, Tagg JR, Ray B (1995) Bacteriocins of gram-positive bacteria. Microbiol Rev 59:171–200

Jindal V, Dhaliwal GS, Koul O (2013) Pest management in 21st century: roadmap for future. Biopestic Int 9(1):1–22

Kah M, Beulke S, Tiede K, Hofmann T (2013) Nanopesticides: state of knowledge, environmental fate, and exposure modelling. Crit Rev Env Sci Tecnol 43:1823–1867

Kalaitzaki A, Papanikolaou NE, Karamaouna F, Dourtoglou V, Xenakis A, Papadimitriou V (2015) Biocompatible colloidal dispersions as potential formulations of natural pyrethrins: a structural and efficacy study. Langmuir 31(21):5722–5730

Kalita DJ, Bhagawati B, Gogoi BB (2012) In vitro efficacy of *Trichoderma* spp. against *Meloidogyne incognita* and *Rhizoctonia solani*. Indian J Nematol 42(1):84–86

Kapsi M, Tsoutsi C, Paschalidou A, Albanis T (2019) Environmental monitoring and risk assessment of pesticide residues in surface waters of the Louros River (N.W. Greece). Sci Total Environ 650:2188–2198. https://doi.org/10.1016/j.scitotenv.2018.09.185

Kawalekar JS (2013) Role of bio-fertilizers and bio-pesticides for sustainable agriculture. J Biofertil Biopestici 2(3):73–78

Keane S, Ryan MF (1999) Purification, characterisation and inhibition of monoterpenes of acetyl cholonesterase from the waxmoth, *Galleria melonella*. Insect Biochem Mol 29:1097–1104

Kefialew Y, Ayalew A (2008) Postharvest biological control of anthracnose (*Colletotrichum gloeosporioides*) on mango (*Mangifera indica*). Postharvest Biol Technol 50(1):8–11

Knowles A (2006) Adjuvants and additives. A grow Reports: T&F Informa UK Ltd. U.S. Environmental Protection Agency, Washington, DC 20460 2008. EPA/600/R-07/045F May 2008, pp 126–129

Kole RK, Banerjee H, Bhattacharyya A (2001) Monitoring of market fish samples for Endosulfan and Hexachloro cyclohexane residues in and around Calcutta. Bull Environ Contam Toxicol 67:554–559

Koul O (2004) Neem: a global perspective. In: Loul O, Wahb SK (eds) Neem today and in the new millennium. Academic Publishers, Springer, Dordrecht

Koul O, Walia S, Dhaliwal GS (2008) Essential oils as green pesticides: potential and constraints. Biopestic Int 4:63–84

Kramer KJ, Mutukrishnan S (1997) Insect chitinases: molecular biology and potential use as bio-pesticides. Insect Biochem Mol 27(11):887–990

Kumar S, Kumar R, Om H (2013) Shelf-life of *Trichoderma viride* in talc and charcoal based formulations. Indian J Agri Sci 83:566–569

Kumar S, Kakraliya SK, Lakhran H, Sheoran S, Ram M, Meena RS (2016) Use of *Bacillus thuringiensis* (Bt) gene: a biotechnological tool for crop improvement. Prog Res An Int J 11 (Special-IX):6247–6251

Kumar S, Jakhar SR, Dahiya S, Jangir CK, Meena RS (2017a) Soil sickness and productivity from ecological aspects. J Pharma Phytochem SPI 6(6S):827–831

Kumar S, Lakhran H, Meena RS, Jangir CK (2017b) Current need of sustainable food and forage production to eliminate food and forage insecurity under current climatic era. Forage Res 44 (1):165–173

Kuppusamy P, Yusoff MM, Maniam GP, Govindan N (2016) Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications – an up dated report. Saudi Pharm J 24(4):473–484. https://doi.org/10.1016/j.jsps.2014.11.013

Luvisi A, Panattoni A, Materazzi A, De Bellis L (2017) Chemical outbreak for tobacco mosaic virus control. Int J Agric Biol 19:792–800. https://doi.org/10.17957/IJAB/15.0365

MacGregor JT (2006) Genetic toxicity assessment of microbial pesticides: needs and recommended approaches. Int Assoc Environ Mutagen Soc:1–17

Mathew SK, Mary CF, Gleena GK, Surindra GD (2011) Antagonistic activity of endophytic *Trichoderma* against *Phytophthora* rot of black pepper (*Piper nigrum* L.). J Biol Control 25 (1):48–50

Mazid S, Rajkhowa RC, Kalita JC (2011) A review on the use of bio pesticides in insect pest management. Int J Sci Adv Tech 1(7):169–178

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena RS, Gogoi N, Kumar S (2017) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359

Meena RS, Mitran T, Kumar S, Yadav GS, Bohra JS, Datta R (2018a) Application of remote sensing for sustainable agriculture and forest management. Inf Process Agric 5:295–297. https://doi.org/10.1016/j.inpa.2018.03.003

Meena RS, Kumar V, Yadav GS, Mitran T (2018b) Response and interactionof *Bradyrhizobium japonicum* and Arbuscular mycorrhizal fungi in thesoybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depthand amendments on soil physical and hydrological properties of anAlfisol in Central Ohio, USA. Geoderma 363:1141164

Mishra K, Sharma RC, Kumar S (2012) Contamination levels and spatial distribution of organochlorine pesticides in soils from India. Ecotoxicol Environ Saf 76:215–225. https://doi.org/10.1016/j.ecoenv.2011.09.014

Mohana DC, Raveesha KA (2006) Anti-bacterial activity of *Caesalpinia coriaria* (Jacq.) Willd against plant pathogenic *Xanthomonas* pathovars: an ecofriendly approach. J Agric Technol 2 (2):317–327

Moore MT, Locke MA, Kröger R (2017) Mitigation of atrazine, S-metolachlor, and diazinon using common emergent aquatic vegetation. J Environ Sci 56:114–121. https://doi.org/10.1016/j.jes.2016.09.009

Morillo E, Villaverde J (2017) Advanced technologies for the remediation of pesticide-contaminated soils. Sci Total Environ 586:576–597. https://doi.org/10.1016/j.scitotenv.2017.02.020

Moscardi F (1999) Assessment of the application of baculo viruses for control of Lepidoptera. Annu Rev Entomol 44:257–289

Mostafalou S, Abdollahi M (2017) Pesticides: an update of human exposure and toxicity. Arch Toxicol 91:549–599. https://doi.org/10.1007/s00204-016-1849-x

Nicholson GM (2007) Fighting the global pest problem: preface to the special Toxicon issue on insecticidal toxins and their potential for insect pest control. Toxicon 49:413–422

Oerke EC (2006) Crop losses to pests. J Agric Sci 144(01):31–43. https://doi.org/10.1017/S0021859605005708

Pascoli M, Jacques MT, Agarrayua DA, Avila DS, Lima R, Fraceto LF (2019) Neem oil based nanopesticide as an environmentally-friendly formulation for applications in sustainable agriculture: an eco-toxicological perspective. Sci Total Environ 677:57–67. https://doi.org/10.1016/j.scitotenv.2019.04.345

Pimentel D (2005) Environmental and economic costs of the application of pesticides primarily in the United States. Environ Dev Sustain 7:229–252

Pinheiroa AC, Bourbona AI, Cerqueiraa MA, Maricato E, Nunes C, Coimbra MA, Vicentea AA (2015) Chitosan/fucoidan multilayer nanocapsules as a vehicle for controlled release of bioactive compounds. Carbohydr Polym 115:1–9

Prakash A, Rao J, Berliner J, Pokhare SS, Adak T, Saikia K (2014) Botanical pesticides for the management of plant nematode and mite pests. In: Advances in plant biopesticides. Springer, pp 89–118

Rajinimala N, Rabindran R, Ramaiah M (2009) Management of bitter gourd yellow mosaic virus (BGYMV) by using virus inhibiting chemical, biocontrol agents, antiviral principles (AVP) and insecticide. Arch Phytopathol Plant Protect 42(8):738–750. https://doi.org/10.1080/03235400701390729

Rangaswami G, Mahadevan A (2012) Diseases of crop plants in India, 4th edn. PHI Learning Private Limited, New Delhi

Rattan RS (2010) Mechanism of action of insecticidal secondary metabolites of plant origin. Crop Prot 29:913–920

Regnault-Roger C, Philogène BJR (2008) Past and current prospects for the use of botanicals and plant allelochemicals in integrated pest management. Pharm Biol 46:41–52

Regnault-Roger C, Philogène BJR, Vincent C (eds) (2005) Bio-pesticides of plant origin. Lavoisier, Paris, p 313

Ritz BR, Paul KC, Bronstein JM (2016) Of pesticides and men: a California story of genes and environment in Parkinson's disease. Curr Environ Health Rep 3:40–52. https://doi.org/10.1007/s40572-016-0083-2

Roser M, Ritchie H, Ortiz-Ospina E (2020) World population growth. Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/world-population-growth

Ross MA, Lembi CA (1985) Applied weed science. Burgess Publishing Co, Minneapolis

Salaheddin K, Valluvaparidasan V, Ladhalakshmi D, Velazhahan R (2010) Management of bacterial blight of cotton using a mixture of *Pseudomonas fluorescens* and *Bacillus subtilis*. Plant Prot Sci 46(2):41–50

Sangeetha A, Kumar PS, Shankar GK (2011) In vitro evaluation of plant products and bio-control agents against *Colletotrichum capsici* causing fruit rot of chilli (*Capsicum annum* L.). Pestic Res J 23(2):164–167

Sardaru P, Anthony JAM, Viswanath B, Narasimha G (2014) Sunflower necrosis disease – a threat to sunflower cultivation in India. Ann Plant Sci 2(12):543–555

Sarwar M (2015) Mites (*Acarina*) as vectors of plant pathogens and relation of these pests to plant diseases. Agric Biol Sci J 1(4):150–156

Schmutterer H (1995) The neem tree and other meliaceous plants, source of unique natural products for integrated pest management, medicine, industry and other purposes. VCH Verlagsgesellschaft mbH, Weinheim

Servin A, Elmer W, Mukherjee A, Torre-Roche RD, Hamdi H, White JC, Bindraban P, Dimkpa C (2015) A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. J Nanopart Res 17:92. https://doi.org/10.1007/s11051-015-2907-7

Shapiro M, Robertson JL, Webb RE (1994) Effect of neem seed extract upon the gypsy moth (Lepidoptera: Lymantriidae) and its polyhedrosis virus. J Ecol Entomol 87:356–360

Sifakis S, Androutsopoulos VP, Tsatsakis AM, Spandidos DA (2017) Human exposure to endocrine disrupting chemicals: effects on the male and female reproductive systems. Environ Toxicol Pharmacol 51:56–70. https://doi.org/10.1016/j.etap.2017.02.024

Singh S, Singh B, Singh AP (2015) Nematodes: a threat to sustainability of agriculture. Procedia Environ Sci 29:215–216. https://doi.org/10.1016/j.proenv.2015.07.270

Singh NS, Sharma R, Parween T, Patanjali PK (2018) Pesticide contamination and human health risk factor. In: Oves M et al (eds) Modern age environmental problems and their remediation, pp 49–68. https://doi.org/10.1007/978-3-319-64501-8-3

Sondi B (2004) Silver nanoparticles as antimicrobial agent: a case study on *E. coli* as a model for gram-negative bacteria. J Colloid Interface Sci 275(1):17–782. https://doi.org/10.1016/j.jcis.2004.02.012

Srinivasan K, Mathivanan N (2009) Biological control of sunflower necrosis virus disease with powder and liquid formulations of plant growth promoting microbial consortia under field conditions. Biol Control 51:395–402

Sriram S, Savitha MJ, Ramanujam B (2010) Trichoderma-enriched coco-peat for the management of *Phytophthora* and *Fusarium* diseases of chilli and tomato in nurseries. J Biol Control 24 (4):311–316

Srivastava A, Trivedi P, Srivastava M, Mohtashim L, Srivastava L (2011) Monitoring of pesticide residues in market basket samples of vegetable from Lucknow City, India: QuEChERS method. Environ Monit Assess 176(1–4):465–472. https://doi.org/10.1007/s10661-010-1597-y

Stevenson PC, Nyirenda SP, Mvumi B, Sola P, Kamanula JM, Sileshi G, Belmain SR (2012) Pesticidal plants: a viable alternative insect pest management approach for resource-poor farming in Africa. In: Koul O, Khokhar S, Dhaliwal DS, Singh R (eds) Bio-pesticides in environment and food security. Scientific Publishers, Jodhpur, pp 212–238

Stillway ME, Hammock BG, Teh SJ (2019) Pesticides in surface water: monitoring, modeling, risk assessment and management. ACS Symp Ser 1308:435–449

Su C, Jiang L, Zhang W (2014) A review on heavy metal contamination in the soil worldwide: situation, impact and remediation techniques. Environ Skept Crit 3(2):24–38. http://www.iaees.org/publications/journals/environsc/online-version.asp

Svetlana Z, Stojanovic S, Ivanovic Z, Gavrilovic V, Popovic T (2010) Screening of antagonistic activity of microorganisms against *Colletotrichum acutatum* and *Colletotrichum gloeosporioides*. Arch Biol Sci 62(3):611–623

UN (2011) World population prospectus: the 2010 revision. UN, New York

UNDES Affairs (2011) United nations department of economic and social affairs. UN, New York

USEPA (1986) Test methods for evaluating solid wastes (SW-846), 3rd edn. Office of Solid Waste and Emergency Response. US Environmental Protection Agency, Washington DC

USEPA (U.S. Environmental Protection Agency) (2008) EPA's 2008 Report on the Environment. National Center for Environmental Assessment, Washington, DC; EPA/600/R-07/045F. Available from the National Technical Information Service, Springfield, VA, and online at http://www.epa.gov/roe

Wani SP, Lee KK (1995) Microorganisms as biological inputs for sustainable agriculture in organic agriculture. In: Behl RK, Khurana AL, Dogra RC (eds) Plant microbe interaction in sustainable agriculture. CCS HAU Hisar and MMB, New Delhi, pp 62–88

WHO (2005) The WHO recommended classification of pesticides by hazard and guidelines to classification 2004. World Health Organisation, Geneva

Xu J, Fan QJ, Yin ZQ, Li XT, Du YH, Jia RY, Xu J, Wang C (2010) The preparation of neem oil microemulsion (*Azadirachta indica*) and the comparison of acaricidal time between neem oil microemulsion and other formulations in vitro. Vet Parasitol 169:399–403

Xu XM, Jeffries P, Pautasso M, Jeger MJ (2011) Combined use of biocontrol agents to manage plant diseases in theory and practice. Phytopathology 101(9):1024–1031

Xu P, Liu Y, Graham RI, Wilson K, Wu K (2014) Densovirus is a mutualistic symbiont of a global crop pest (*Helicoverpa armigera*) and protects against a baculovirus and Bt bio-pesticide. PLoS Pathog 10(10):1–11

Yu H, Li F, Yu W, Li Y, Yang G, Zhou S, Zhang T, Gao Y, Wan H (2013) Assessment of organochlorine pesticide contamination in relation to soil properties in the Pearl River Delta, China. Sci Total Environ 447:160–168. https://doi.org/10.1016/j.scitotenv.2012.12.070

Zaganas I, Kapetanaki S, Mastorodemos V, Kanavouras K, Colosio C, Wilks MF, Tsatsakis AM (2013) Linking pesticide exposure and dementia: what is the evidence? Toxicology 10:3–11. https://doi.org/10.1016/j.tox.2013.02.002

Precision Farming for Resource Use Efficiency

4

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Abstract

Globally, agriculture remains one of the primary occupations of citizens supporting more than one-third of the human population. Only 17% of global agricultural land is irrigated that produces 40% of food resources. Several factors threaten the agricultural production systems all over the world. These mainly include population explosion, industrialization, competition to the primary agriculture sector by the secondary and tertiary sectors, limited resource bases, and land degradation. The demand for water resources is projected to increase by 60% by the year 2025. Around 44% of agricultural land in India is facing problems of land degradation due to different causes. In the modern era, the concept of precision farming (PF) has gained much importance as it possesses the potential to improve yields using minimum inputs while keeping the environment sustainable. Precision farming refers to the process of maneuvering, with improved accuracy, over the inputs and practices to fine-tune with the local prevailing conditions for maximization of outputs with minimum resource/input use. Precision farming revolves around three basic steps, i.e., capturing variability, analyzing variability, and finally decision making. Precision farming aims to prevent land degradation, resource depletion, and environmental degradation and thus improve livelihood. The concept of PF is equally applicable in different branches of agriculture as well as in animal husbandry. Different technologies make up the very core of PF. These mainly include global positioning system (GPS), geographical information system (GIS), remote sensing, variable rate application (VRA), Internet of Things (IoT), and robotics. Resource use efficiencies are the important advantages of PF, which include water use efficiency, soil use efficiency, nutrient use efficiency, energy use efficiency, and other efficiencies. Around 185 million tonnes of fertilizers are used annually which cause different issues to environment and agriculture when used non-judiciously. Under PF, nitrogen-use efficiency has been reported to increase by 368%. Additionally, drop in nitrogen residues up to 30–50% levels has also been reported. The other added advantage is environmental protection and sustainability. Variable irrigation under PF can reduce up to 25% water usage in an agricultural field. In this chapter, we have attempted to elaborate on PF in agriculture, related aspects, advantages, and associated resources use efficiencies.

Keywords

Management · Precision farming · Resource use efficiency · Sustainable · Technology · Variability · Variable-rate application

Abbreviations

FMIS	Farm management information system
GHGs	Greenhouse gases
GIS	Geographical information system
GPS	Global positioning system
IoT	Internet of Things
PF	Precision farming
UAVs	Unmanned aerial vehicles
UNESCO	United Nations Educational, Scientific, and Cultural Organization
VRA	Variable rate application

4.1 Introduction

Agriculture remains one of the main enterprises all around the world, especially in the developing nations. The share of the primary sector (mainly agriculture and allied sectors) in the gross domestic product (GDP) of various nations is decreasing while the share of secondary and tertiary sectors is increasing with each passing day. The major problems hampering agriculture all over the globe include that of declining productivity, reducing natural resources, decreased profitability, environmental degradation, marginal landholding, and global climate change (Reynolds et al. 2015; Kumar et al. 2016; Bajiya et al. 2017; Lakhran et al. 2017; Meena et al. 2017a). Agricultural production is threatened by population explosion, increased pace of agricultural land conversion, environmental sensitivity and rapid environmental degradation, changing food habits, and unequal distribution of resources, especially irrigation water (Nath et al. 2015). The increased population has forced farmers all over the globe and especially in developing countries to adopt resource intensive farming coupled with unsustainable practices and indiscriminate and non-judicious use of available resources (Shanwad et al. 2002). According to an estimate, water demands are projected to increase by 60% by the year 2025 (Boretti and Rosa 2019). Around four-fifths of freshwater resources on earth are used for irrigation purposes in agriculture (Evans and Sadler 2008). More than the amount, distribution of resources is uneven that ultimately hampers the agricultural production systems from being efficient (Vollrath 2007). Future wars may be fought on water and other resources. With rising input costs, increased threat to environmental stability, and high pressure for sustainable agriculture, there is an increased need felt for optimizing resource use efficiency (RUE) in modern agricultural systems (de Wit 1992; Kakraliya et al. 2018). Since the beginning of agriculture, humans have always yearned for improved activities and techniques to minimize the inputs and maximize the outputs. With increasing population and phenomenon of global climate change, agriculture feels immense pressure for increased production and profitability with minimal damage to the environment. There remains tremendous scope for optimizing the use of inputs like fertilizers, pesticides, herbicides, water, seed input, available land, and labor, especially in the developing countries

(Goulding et al. 2008). The demand for these inputs is increasing at a tremendous rate and increased usage adversely affects the environmental stability and sustainability (Pretty and Bharucha 2014).

In India, besides the contribution from growing improved crop varieties, the green revolution was attainable mainly due to the intense use of chemical fertilizers, herbicides, and pesticides (Sebby 2010; Meena et al. 2020a). The same led to environmental degradation and decreased sustainability of the outputs (Pingali 2012). In the modern era, agriculture faces multiple challenges in improving productivity through considerable margins without any adverse effect on environmental conditions. Precision farming (PF) provides a potential answer to these problems aiming at increased production, less resource usage, and sustainable environmental usage and protection. In this chapter, we have attempted to discuss different aspects of PF and RUE in the modern era.

4.2 Precision Farming

Globally, several definitions have been attributed to the process of PF. These vary depending on the regional identities, crop patterns, agriculture and allied sectors, and so on. However, a definition to near-universality defines it as maneuvering, with improved accuracy, over the inputs and practices to fine-tune with the local prevailing conditions for maximization of outputs with minimum resource/input use. Precision farming involves the application of appropriate technologies to capture spatial and temporal variation in agricultural fields with the ultimate aim of improving productivity, judicious use of input resources, and making environment sustainable (Garibaldi et al. 2017; Rees et al. 2017). The concept of PF was pioneered in the 1980s, while its application at a commercial scale was started in the 1990s (Finger et al. 2019; Gomiero 2019). Precision farming is primarily aimed at making agriculture as low-input, high-efficiency, and sustainable venture (Mondal and Basu 2009). Agricultural fields differ in various characteristics including potential yields, nutrient and moisture content of the soil, topography (land levels), pest and disease occurrence, and lodging susceptibility (Van Ittersum et al. 2013). Based on these characteristics, a single field of agricultural land can be divided into different heterogeneous zones (called management zones). Each management zone is handled differently according to its characteristics. Instead of applying inputs and managing an agricultural field or an animal farm based on some average value (that may not even be existent in the whole field/farm), PF is based on site- and time-specific approaches (Singh 2010). Precision farming depends highly on data generated at preliminary stages about crop(s) grown, soil type(s) and nutrient content, distribution of pests, micro and macro environmental parameters, and trends (Wolfert et al. 2017). The data generated helps to optimize output to best potential and encourage sustainability without disturbing the environmental parameters. Precision farming can be practiced at various scales and levels, starting from marginal farmers to organized large farms, from conventional to organic farms, in developing as well as developed countries (Finger et al. 2019). The type of intervention, distribution, and extent of treatment(s) may also vary depending on various factors that include the size of field/farm, the economics of the field/farm, and previous experience of the farmer/manager.

4.2.1 Need for Precision Farming

Two types of yields exist for any farming activity with any crop/livestock, i.e., actual present yield (realized) and potential yield (Mayberry et al. 2017). The corresponding difference between the two yields is called as yield gap. There exist several factors, some tangible while others being intangible, that affect the ultimate crop yield (Van Ittersum et al. 2013). Before starting PF, the factors affecting yield are analyzed and classified based on various criteria like minor and major factors *vis-à-vis* the yield; tangible and intangible factors; cost-effective and cost-ineffective factors, and so on. Based on the detailed analysis of these factors, remedial management measures are planned for improved yields. Decisions are made about the type of intervention being undertaken along with their distribution and extent. Following reasons mainly emphasize on the need for the application of PF in present agricultural systems (Fig. 4.1):

4.2.1.1 Prevention of Land Degradation

Land degradation is one of the main problems in modern agriculture, especially in developing countries (Gupta 2019). The problem of land conversion for purposes other than agriculture is a global issue (Peerzado et al. 2019). Land degradation is attributed to many different causes that mainly include overuse, deforestation, industrialization, increased and indiscriminate use of agrochemicals, soil erosion, and climate change (Bhattacharyya et al. 2015). Precision farming aims to reduce the degradation of soil resources by adopting holistic measures so that soil resources are adequately supplemented with adequate inputs and excess exploitation is prevented (Gomiero 2016).

4.2.1.2 Preventing Depletion of Resource Base

Worldwide, the resource base is highly threatened via non-judicious and unsustainable usage (Struik and Kuyper 2017). There is an urgent need for conserving

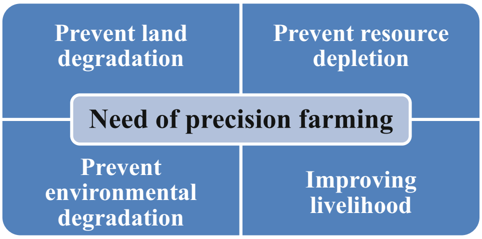

Fig. 4.1 Main reasons that stress the need for the adoption of precision farming

resources. The changing agroclimatic trends increase the pressure on the resource base and threaten the existence of agricultural production systems. In the current era, stress is more equivocally given to increase food production along with greater environmental security through sustainable ways (Shah and Wu 2019). Precision farming possesses the potential to relieve some of the pressure from the resource bases and conserve them for sustainable futuristic use (Bongiovanni and Lowenberg-DeBoer 2004).

4.2.1.3 Preventing Environmental Degradation

The present agricultural production scenario demands the maintenance cum promotion of environmental stability and sustainability (Bhan and Behera 2014). Environment and atmospheric conditions are highly sensitive and are continuously threatened by increased mechanization, industrialization, and increased greenhouse gas (GHG) emissions from various sources (Mgbemene et al. 2016). Under PF, a holistic approach is applied that ensures minimum pollution of environmental resources and promotes its sustainability (Lindblom et al. 2017).

4.2.1.4 Other Factors

Other factors that necessitate the adoption of precision farming include the challenge of cost dynamics, problem of agrochemical residues in water and land (Bongiovanni and Lowenberg-DeBoer 2004), and ultimately targets of poverty alleviation and improvement in livelihood (Jenrich 2011). Precision farming aims to produce a perfect amalgamation of different steps to promote activities that are beneficial to farmers, and overall sustainability of resource base and environment (Bach and Mauser 2018).

4.3 Steps in Precision Farming

There are three important steps in any PF venture and these include capturing variability; evaluating variability; and finally, decision making (Shafi et al. 2019). Figure 4.2 depicts the entire cycle of PF. All these steps revolve around three critical pillars, i.e., information, technology, and management.

4.3.1 Capturing Variability

Precision farming is associated with managing the inputs according to the variability of different factors affecting the final yield concerning time and space (Kitchen and Clay 2018). It is very difficult to introduce any management strategy without knowing the underlying spatial and temporal variability. However, both spatial and temporal variability are rarely collected concurrently (Dornelas et al. 2013). In PF, the heterogeneity in different aspects of soil, weather, and others decides the steps in input management. Various characteristics like moisture and soil content, temperature, topography, weather, lodging susceptibility, nutrient content, pest

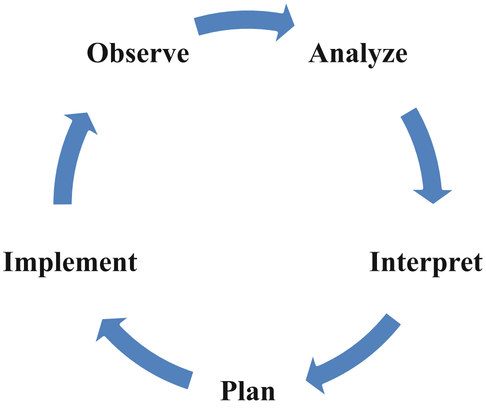

Fig. 4.2 A complete cycle of precision farming

occurrence, etc. are assessed at the initial stages of PF. Different maps are prepared based on variability within and between the fields. Properly locating variability and adequately quantifying it via mapping are crucial for overall success in any PF venture (Kumar et al. 2017).

Agricultural inputs in terms of seeds (sowing), application of fertilizers and pesticides, and others affect the ultimate yield. Sowing time (early vs late) also affects the ultimate yield (Ozturk et al. 2008). Sowing time determines the conditions to which the crop(s) will be subsequently exposed. The crop will cross through different developmental stages and some environmental factors will either support or defy the development at critical points. It ultimately affects the yield in terms of its quality or quantity or both (Alberio et al. 2015). Leveling of land before sowing also affects the yield of a particular crop (Naresh et al. 2014). Similarly, there are several macro and micro characteristics that affect the ultimate yield of a crop. These factors may pertain to the soil, its physical, chemical, or biological characteristics or environment (weather, parasites, disease occurrence, precipitation, etc.) or any other factor. The soil in terms of its texture, moisture, humus, topography, and landscape status also affect the yield (Maslaris et al. 2010). In PF, variability in the agricultural field is assessed using appropriate tools and techniques. The data related to various aspects affecting the ultimate yield (directly or indirectly) are collected. Capturing entire variability can be challenging and thus appropriate technologies need to be used for this purpose. Data collection can be made using survey technique, census or sampling, using satellites and other technologies, interpolation or extrapolation techniques, modeling, sensor-based, or others (Shibusawa and Haché 2009). Some of these technologies are described later in this chapter. Information can also be collected from secondary sources regarding the total field, its soil profile and surroundings, weather and irrigation patterns, weed, pest and insect occurrence, and others.

4.3.2 Evaluating Variability

Precision farming aims to make agricultural activities temporally and spatially precise. The heterogeneity in an agricultural field defines the time-specific and site-specific management steps (Finger et al. 2019). Once the variability capturing process is efficient and all of it assessed, it becomes easy and economical to manipulate and manage various agricultural inputs for efficient farming. It is easy to manage the inputs for maximal output when variability exists either with space or time only because their interaction makes the situation complex (Ali 2013). With PF, the fertilizers and pesticides will be applied in site-specific quantities at appropriate times and according to the needs of soil and crop involved (Pedersen and Lind 2017). Thus, heterogeneity of edaphic, weather, and other factors plays an important role in deciding input factors in PF. The data generated in the initial step of PF needs to be evaluated for meaningful interpretations and decisions. Different statistical tools and software, mathematical algorithms are used to arrive at meaningful conclusions from the data obtained (Oliver 2013; Panayi et al. 2017).

4.3.3 Decision Making

Conventional farming is based on universal input support for growing different crops. Fertilizers, herbicides, fungicides, and pesticides are applied at uniform rate irrespective of soil characteristics in terms of nutrient content and need for chemical application. Similarly, irrigation water is provided at a wholesome rate irrespective of moisture content, and soil and crop requirements. However, in PF, inputs (fertilizers, pesticides, herbicides, fungicides, seed input, irrigation water, etc.) are used meticulously according to the local factors applicable (Adamchuk 2010). Fertilizers can be applied based on the nutrient content of soil and the needs of the crop (Dong et al. 2012). Similarly, herbicides can be applied based on the data on the weed density of a particular crop grown at a specified place. The same rule applies to the application of other inputs. Being temporally precise implies taking appropriate decisions based on the applicable time factors. For instance, depending on the analysis of different applicable factors, appropriate timing shall be decided on when to go for a particular activity like weed control, irrigation, apply different chemicals, and so on.

Overall, the previous three steps are aimed at ensuring the exercises of site-specific planting and land, nutrient and weed management, irrigation, pest and disease control measures, etc. There are two types of systems for manipulation of input in terms of type, quality, quantity, and other aspects, i.e., ones that produce a direct effect and others that produce an indirect effect on overall profitability and sustainability. Both manipulations should be explored and exploited optimally to obtain maximum profits.

4.4 Technologies in Precision Farming

Precision farming is a technology-driven revolution aimed at maximizing output while optimizing the input/resource use (Bakhtiari and Hematian 2013). These technologies make the main heart of PF with their efficient working leading to profitable enterprises. Any farmer before employing PF needs to understand the working of various hardware, software, and decision support systems (Erickson et al. 2018). Various technologies used in PF include global positioning system (GPS), remote sensing, geographical information system (GIS), robotics, drone technology, sensor technology, Internet of Things (IoT), global navigation satellite system (GNSS), management information system (MIS), farm management information system (FMIS), and variable rate application (VRA) (Harrington 2016; Shafi et al. 2019; Tantalaki et al. 2019). The list of technologies that are useful for efficient PF venture is not exhaustive.

Different technologies are useful for improved accuracy and efficiency in PF (Far and Rezaei-Moghaddam 2018). The primary aim of any technology in PF is to assess the current crop condition, delineate different heterogeneous zones from each other, and finally recommend appropriate management steps after data analysis. These technologies primarily focus on assessing the temporally and spatially specific dimensions of an agricultural field/crop (Hedley 2015). Using different technologies, abundant data is generated and subsequently analyzed related to crop biomass, crop health, distribution, lodging susceptibility, water level, temperature, etc. Ultimately, decisions are made as to what parameters should be managed at what time, in what amount and direction to get a healthy and profitable crop. The PF technologies mainly involve three categories of equipments, i.e., (1) hardware and sensors, (2) data analysis and decision support systems, and (3) commodity-focused systems (Balafoutis et al. 2017). Figure 4.3 summarizes the purposes of various technologies used in PF.

4.4.1 Geographical Information System

The geographical information system (GIS) is one of the important technological parts for the successful implementation of PF (Yousefi and Razdari 2015). It helps to generate the spatial maps representing data about the variability in an agricultural field. In GIS, the hardware component may range from the simple handheld unit to satellites and drones (Sood et al. 2015). Using GIS, variability is explored regarding soil type, moisture content, rainfall amount, topography, leaching, lodging, erosion, elevation, and other aspects of an agricultural field. All data generated helps farmers/managers to make informed decisions about appropriate management measures to be taken up. This data also allows a farmer to guide control over mechanical operations such as harvesting, tillage, and agrochemical application. Geo-referencing sensors are needed to optimize the functioning of GIS whereby maps regarding yield, nutrient and moisture content, soil salinity, etc. are also assessed (Hackeloeer et al. 2014). Informed decisions related to crop management, selecting suitable sites for

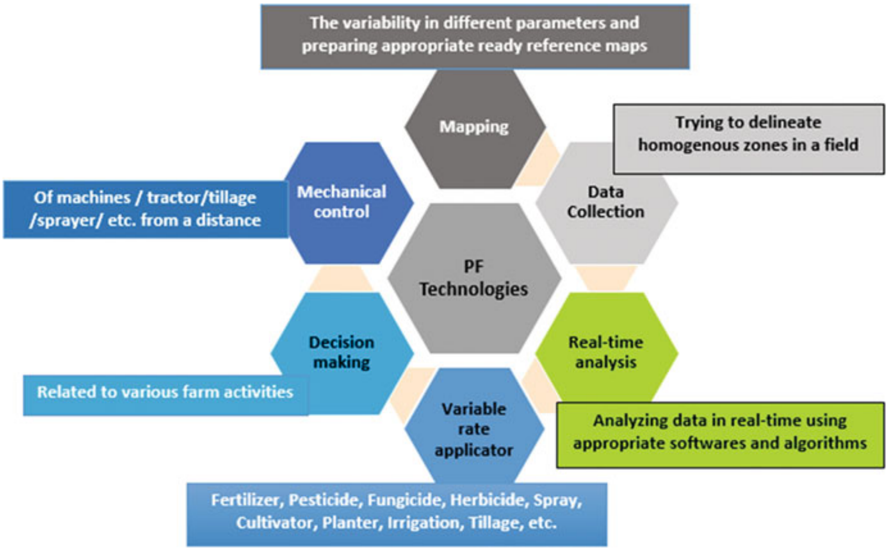

Fig. 4.3 Purpose of various technologies used in precision farming

cropping, managing low and high drainage areas. Preventive and rescue measures can be planned effectively and implemented in times of flood, drought, soil erosion, leaching, lodging, and disease/pest damages.

4.4.2 Global Positioning System

Global positioning system (GPS) is radio-navigation based system working on satellite signals which is capable of providing continuous three-dimensional (3D) signals (longitude, latitude, and elevation) about the agricultural land and crops grown (Yousefi and Razdari 2015). GPS is a technology useful for determining the exact location (regarding any event/aspect) in an agricultural field with considerable accuracy. GPS has improved accuracy in terms of recording coordinates regarding position, time, and direction with reliability (Shanwad et al. 2002). In the modern era, major farm operations are computerized with the use of unmanned aerial vehicles (UAVs) and robotics. The UAVs have been found highly useful in small fields with image resolutions up to a centimeter range (Candiago et al. 2015; Finger et al. 2019). With UAVs, analysis of different traits is made possible which includes crop biomass, nutrient composition, photosynthetic efficiency, etc. Furthermore, UAVs can also be useful in thermal scanning of crops, data generation about the electrical conductivity of field and for sampling purposes (Corwin and Lesch 2005). Uncorrected GPS signals possess an accuracy of up to 300 feet (Singh 2010). Afterwards, differential corrections are made based on the land- or satellite-based signals and the accuracy is thereby improved. In PF, GPS also helps in managing farm mechanical processes with optimal localization accuracy (Yousefi and Razdari 2015). Accurate guidance cum navigation will help in many aspects, i.e., improving the efficiency of mechanical processes, assess the conditions at the ground in real-time, assess weather conditions, etc. GPS mapping devices can either be taken manually to the field or mounted on the agricultural implements (Shannon et al. 2020). Data is generated regarding the various factors including soil moisture and pH, nutrient composition, previous performance in terms of yield, etc. and the same can be used for making efficient and informed decisions.

4.4.3 Remote Sensing

Remote sensing refers to a technology that helps to collect information from above the earth's surface at a distance through a non-invasive technique, i.e., without actual handling and manipulation of the object (Mountrakis et al. 2011). Different remote sensors can be used in precision agriculture including satellite and aerial imageries, ground sensors (optical or reflective), chlorophyll sensors, soil scanners, canopy scans, weed detectors, and others. Remote sensors record energy that is reflected or emitted from the earth's surface. Satellites, aircraft, and drones are useful for collecting information. It mainly works at capturing different spectra of light, both in visible and invisible ranges (Aggarwal 2004). Based on temperature differences of the surface, intensities and wavelengths of lights emitted/radiated differ and calculations are made regarding the plant biomass, nutrient composition and deficiencies, moisture levels and water stress, disease/pest occurrence, the maturity of fruits, etc. This technology is used to collect many types of information from agricultural fields ranging from soil quality to leaf chlorophyll content. Plant stress can also be assessed using remote sensors by monitoring moisture, nutrient content, compaction, chlorophyll content, and disease symptoms. The nutrient and water content of soil of a particular region is assessed using remote sensing and corresponding decisions are made regarding the agricultural patterns to be followed on such land. For instance, based on the nitrogen content of the soil, a particular crop may be grown or fertilizer application may be optimized for higher yields. Similarly, based on water content and other soil properties, drip irrigation or sprinkle-based irrigation may be followed for optimal water resource usage and maximal yields. Based on these adjustments in inputs, the yield is maximized with the least damage to the environment.

Shafi et al. (2019) have reported different kinds of sensors used for measuring different parameters in plants. Different kinds of sensors have been implemented in the field till now that measure soil temperature, soil salinity, soil moisture, conductivity, plant temperature, plant moisture, plant wetness, photosynthesis, carbon dioxide (CO_2) and hydrogen levels, air temperature, air humidity, barometric pressure, and so on. Ultimately, based on data generated, efficient management steps are taken with respect to the usage of fertilizers and other agrochemicals, deciding the rate of seeding and nursery application and other inputs.

4.4.4 Variable Rate Application

In an agricultural field, different management zones may vary concerning their needs for various inputs like fertilizer, seed sowing particulars, irrigation water, agrochemical application, and others. However, it is nearly impossible to detect and disperse these variable needs based on mere observation. Therefore, variable rate technology (VRT) has recently emerged to accurately disperse the inputs according to the individual requirements of a particular crop grown on a specific agricultural field. Based on soil characteristics, the seed sowing density may need to be changed for optimum and maximized yields. Similarly, based on nutrient characteristics of soil, fertilizer application can be maneuvered for maximizing outputs. The VRA economizes farming by optimizing the input use and maximizing the outputs by differentiating between different management zones within the same agricultural field (Krishna 2019).

Variable-rate technology techniques can be either map-based or sensor-based. Map-based systems adjust the application rate based on a map (electronic or prescription). Here, map preparation is necessary which needs increased efforts and time. Whereas, the sensor-based maps use a real-time approach, using a continuous stream of data, without using any maps or positioning systems. Here, instead of map preparation, data are generated in real-time and decisions are made after its analysis. Based on real-time information gathered using sensors, adjustments regarding the application of inputs are done. No prior mapping is required in the case of sensor-based VRA; however, it cannot be useful for future references as against map-based data. Sensor-based VRA can be either an active or passive system. In an active system, signals are continuously generated and pointed towards an object and returning signals are received, processed, and analyzed. However, the passive system depends on some accessory stimulus and changes created thereof. Of the two, active sensor systems work more efficiently. Each method has its pros and cons (Van Loon et al. 2018) and combining both into single equipment may solve many problems.

The VRA technique can be used for various purposes including seeding, weed control, lime application, fertilizer application, chemical spraying, etc. Initially, different heterogeneous tracts are identified and their characteristics studied. Subsequently, variable-rate applicator disburses the input based on the actual need of that zone.

Besides above, recently robotic weed management is gaining momentum under ventures of PF. Another technology, IoT, is a set of computerized networks which works on automated analysis from capturing of signals to ultimate decision making. The FMIS is another computerized system that captures, stores, processes, and disseminates the data in a particular format into the database. It is noteworthy here that it would not be feasible to implement all the technologies in a single field/farm. However, after appropriate analysis, a set of few technologies may be selected and implemented in the field for better results. The selection and implementation of these technologies will depend on various factors including size and other characteristics of the field, economics, previous experience, and contemporary implementation by other farmers in the vicinity.

4.5 Precision Farming in Livestock

Besides agriculture, the concept of PF is equally applicable in livestock farming systems. PF is aimed at improved livestock productivity (production per head per unit time) based on automated technologies that help capture and proper analysis of information (Banhazi et al. 2012). In livestock, PF is aimed at real-time monitoring and decision making with regard to animals' health, production, reproduction, and welfare aspects along with continuous environmental assessment. Precision dairy farming refers to a dairy farming management system that is driven by information and communication technology to capture, evaluate, and manage variability for overall sustainable performance and profitability. Under precision dairy farming, physiological, pathological, behavioral, and management aspects are evaluated and indicators are recorded for analysis and decision making. The management practices are maneuvered based on the behavior and performance of animals in that particular system. In the conventional farming system, management decisions were dependent entirely on the observation and experienced judgment of the farmer (Frost et al. 2003). However, with modern technologies, animals can be examined continuously for various purposes with no major labor requirements. Based on this, individual animals can be examined for signs and symptoms of a disease, oestrus and behavioral manifestations, feeding, movement, rumination, etc. that can help start appropriate and early interventions in terms of management or therapy. This has served two things, i.e., decreased the labor requirements in the farming system and allowed large organized farms to be established with minimal labour requirements. Precision dairy farming is hugely dependent on image, sound (microphone based), and sensor-based analysis. Based on data collection and analysis thereof, farmers get alerts whenever and wherever the intervention is needed.

Automated technologies are used in precision dairy farming which help replace the human personnel requirements. The main aims of precision dairy farming include (1) increasing performance and productivity, (2) recording the normal physiological activities of animals like feeding, rumination, movement, etc., (3) diagnosing the disease at the earliest possible time, (4) easy oestrus detection and thus extending the productive and reproductive lifespan of animals, and (5) employing preventive measures for disease management as against medicinal treatment. In precision dairy farming, technologies are used for milk yield recording, measurement of fat/solid not fat (SNF)/somatic cell count (SCC), body condition scoring, determining the oestrus states of animals, and so on. Overall, based on variability scored, informed decisions are made by farmers/managers, leading to improved performance.

Physiological monitoring of dairy animals possesses a great potential in supplementing the art of a skilled farmer and improving its livelihood (Thornton

2010). Using technologies in PF, it is possible to manage large herds with a relatively lower number of workers. The first thing needed in PF is knowing the overall variability in physiological parameters through which the abnormal manifestations can be noticed. Two things determine the eventual production/reproduction performance of an animal, i.e., its genetic potential and the environment it is reared in (Rauw and Gomez-Raya 2015). The same animal, when reared in two different environments, performs differently. This variability is generated entirely because of environmental conditions. The genetic potential of an animal can be exploited to the maximum possible extent by providing the optimum environmental conditions. The environmental conditions include nutrition, stress-free environment, management and housing, climate, etc. Understanding the different aspects of the interaction between genetic makeup and environmental conditions is essential before any intervention is made. Therefore, there is an utmost need to create an environment that facilitates performance up to the genetic potential of an animal. This attains more importance in the present era of global warming and climate change. Based on the response of animals to different environmental conditions, normal and abnormal responses can be efficiently stratified. Potential benefits of PF in livestock include increased efficiency of resource use, improved performance, product quality and health, increased environmental sustainability, etc. Overall, there is a positive impact on production, reproduction, health, and quality control aspects of livestock farming. However, the benefits and their realization are more in large herds than smallholding farms.

Information and communication technologies, when integrated with farming practices, need integration, efficient analysis, and interpretation for meaningful results. An additional benefit of using information technology under precision livestock farming is the understanding and analysis of functional traits in animals. Functional traits are those traits that have no direct market value but affect the productive and reproductive performance of animals indirectly. For example, longevity is one such trait that affects the productive and reproductive performance of an animal by prolonging its lifespan. In precision livestock farming, traits other than production and reproduction ones can be recorded and accordingly appropriate decisions *vis-à-vis* their breeding and management can be made.

4.6 Advantages of Precision Farming

Precision farming is attractive and advantageous to both the farming community and society overall. Precision farming benefits farmers directly by improving the yield with respect to their quality and quantity. Indirectly, owing to the lesser investment on input usage, the farmer gets benefited. Though sometimes, the initial cost of establishment of technologies may seem high; however, it normally gets compensated with savings from lesser input costs. By applying PF while keeping heterogeneity of different in mind, farmers are blessed with a uniform yield that can fetch better yield for commodities in the market.

Increased consciousness among people regarding hygiene and environmental sustenance demands for the application of PF at most of the places. Precision farming benefits the whole society by making agriculture sustainable and environment friendly. Water, soil, and air quality will be enhanced with the help of PF. Under PF, this all is possible while staying economically profitable and feasible. Mostly, while quantifying the benefits of PF, the costs of environmental reimbursements are ignored. However, it is not necessary that in all PF ventures both output sustainability and environment protection can be attained. Furthermore, the nature of environmental protection is not so simple because various factors play their part. For instance, under PF, herbicide application is minimized leading to less damage to the environment but mechanical interventions may lead to increased pollution in other forms like carbon footprints, GHGs emissions, etc. Overall, PF is beneficial in terms of productivity improvement, reduced production costs, efficient decision support systems, reduced environmental impact, and sustainable agriculture. The present status, future perspectives, and role of precision farming towards improving resource use efficiency are highlighted in Table 4.1.

4.6.1 Resource Use Efficiency

Agricultural farming is hugely dependent on inputs like water, seed, fertilizer, land usage, etc. In the modern era, resource crunch is one of the huge limiting factors with respect to agricultural production. In recent decades, improvement in production has been assured based on genetic manipulation cum improvement, extensive use of agrochemicals, improvement in farm machinery (training and testing), and others. However, in the near future, resource bases will be under tremendous pressure and nearly exhausted and it may ultimately threaten the production of agricultural products. According to an estimate by UNESCO (2006), cropping intensity needs to increase by 40% above the present state to feed the ever-increasing population by 2030. For reaching near to these targets, irrigation supply shall also increase by about 14% above the present levels (UNESCO 2006). There is an utmost need to make sustainable use of available resources at present so that they are available for future generations. Precision farming is also aimed at promoting RUE *vis-à-vis* agriculture and allied sectors. In PF, research and extension activities are aimed at improved activities. These include the selection of seed germplasm, land selection and preparation, appropriate management at different development stages of crops, efficient irrigation, harvesting and post-harvesting management steps, etc. With passing time, the technologies used will be cheaper and efficiencies will improve, thereby improving the cost-benefit ratio of PF. According to a study by Balafoutis et al. (2017), herbicide usage can be reduced even up to 90% under PF (versus conventional farming). Similarly, pesticide usage can be reduced by up to 25% under PF (Kempenaar et al. 2017). In another report, insecticide usage using PF-based technologies in a wheat field has been reported to improve production status by more than 13% (Dammer and Adamek 2012). Different resource use efficiencies are discussed individually below:

Table 4.1 Precision farming—present trends, future perspective, and resource use efficiency

Type	Remarks	Reference
Present status	44% of total agricultural land in India facing land degradation problem	Mythili and Goedecke (2016)
	185 million tonnes of fertilizers used annually in agriculture	Shannon et al. (2020)
Future projections	40% increase in cropping intensity needed by 2030	UNESCO (2006)
	14% increase needed in irrigation supply	UNESCO (2006)
Resource use efficiency and improved production in precision farming	Up to 90% reduction in herbicide use	Balafoutis et al. (2017)
	Up to 25% reduction in herbicide use	Kempenaar et al. (2017)
	Water usage reduced by about 25%	Evans et al. (2013)
	Up to 13% increase in overall yield	Dammer and Adamek (2012)
	Cost saving up to 44% of total value of additional N-fertilizer applied	Good and Beatty (2011)
	368% increase in nitrogen-use efficiency along with 10–80% less N-fertilizer use and drop in residual nitrogen levels by 30–50%	Diacono et al. (2013)
	5–25% less expenditure on fuel usage	Shockley et al. (2011), Jensen et al. (2012)
	34% reduction in emission of nitrogen oxides	Sehy et al. (2003)
	Profit in 68% cases of PF	Griffin and Lowenberg-DeBoer (2005)
	10–20% savings on use of GIS, GPS, and sensor technologies in PF	Hedley (2015)

4.6.1.1 Water Use Efficiency

Water is the main input required for irrigation purposes and is one of the main limiting factors for maximizing agricultural produce. Under conventional farming, the irrigation process is followed in all or none principle. However, mostly, the irrigation water resources are limited. According to an estimate, only 17% of global agricultural land is irrigated that produces 40% of food resources globally. However, problems of soil salinity, waterlogging, and erosion complex the availability of irrigation water. Another big issue regarding water availability for irrigation is its irregular distribution. The situation is expected to worsen in arid and semi-arid regions of the world. Water use efficiency is thus highly significant in ensuring the maximum returns.

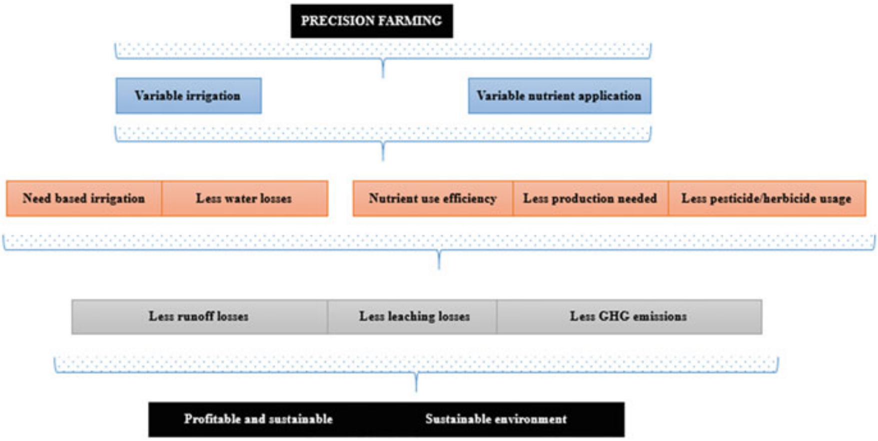

Fig. 4.4 Precision farming *vis-à-vis* variable irrigation and nutrient application

Precision farming promises an efficient irrigation system for agricultural fields. Different kinds of soils differ in their characteristics regarding their texture, porosity, water-retaining capacity, etc. Management zones are assessed for these characteristics and accordingly, the maps are prepared based on electromagnetic signals (Hedley 2015). After analysis, soil characteristics regarding irrigation potential and needs are derived and supplies are managed accordingly. Variable irrigation (Fig. 4.4) under PF can reduce up to 25% water usage (Evans et al. 2013). In PF, irrigation efficiency is increased based on the analysis of specific spatial and temporal needs of field and crops. Accordingly, variable rate applicators are put in place which help in efficient irrigation management of crops with minimum wastage of resources (West and Kovacs 2017). Irrigation efficiency is also aimed to reduce the losses of water from agricultural fields through runoff water (up to 55%), transpiration evaporation from plant surfaces, and evapotranspiration (Allen et al. 2003; Hedley 2015). Sensor-based technology and VRA in PF help reduce the depletion of groundwater resources. Precision farming also helps to reduce costs of production indirectly by reducing pumping costs, conserving water resources, and making agricultural production more intensive (West and Kovacs 2017; Kumar et al. 2017a, b, c). Appropriate technologies for efficient irrigation mainly include micro-irrigation procedures like a drip-, sprinkle-, and micro-sprinkle irrigation systems (Gupta and Kumar 2018; Dahiya et al. 2018; Kumar et al. 2019). Other technologies include multi-user electronic hydrants, variable speed pumps, sub-surface drip irrigation, regulated deficit irrigation, etc. (Levidow et al. 2014). The agricultural produce may be maximized substantially using effective water management practices.

Under PF, irrigation water is applied at the right place, at the right time, and in appropriate amounts only. There is an urgent need to redesign the irrigation systems all over the globe so that water efficiency is increased. Recycling and reuse of wastewater along with the prevention of water evaporation can be useful for the conservation of water and its potential use for other uses. Other aspects include using water-use efficient crops in arid and semi-arid areas and developing crop varieties that are efficient regarding irrigation water usage. Besides improving the quality of surface waters, there are additional benefits in using variable rate irrigation, which include minimizing the nutrient, sediment and fertilizer runoff, and contamination of underground water resources (Sadler et al. 2005; Neupane and Guo 2019).

4.6.1.2 Soil Use Efficiency

Soil makes one of the basic necessary resources on which whole agricultural production is dependent. To ensure sustainability in production, soil health needs to be ensured in terms of its physical, chemical, and biological properties (Meena et al. 2018, 2020b). Any improvement in produce at the expense of soil properties is eventually a huge loss. Using measures aimed at improved yields but leading to loss of fertility nullify the overall profits. It takes considerable time (500–1000 years) for the natural formation of the topmost soil layer. Once this layer is eroded or lost, it is impossible to repair it within shorter periods thereafter. According to an estimate, around 44% of total agricultural land in India is facing land degradation problems in one or other forms (Mythili and Goedecke 2016).

Agricultural fields are composed of different kinds of soils with different properties and nutrient contents. Conventional sampling and lab analysis for soil properties is time-consuming and may not yield optimal results. In conventional methods of sampling and testing, inaccuracies occur due to various reasons, i.e., inaccuracies generated during wet-lab experimentation, reduced measures due to soil respiration during transport and processing, etc. Using different technologies to detect soil properties removes major shortcomings of conventional methods. Through remote sensing, the soil analysis is made accurate, cheaper, and less laborious. In PF, techniques like hyper-spectral imaging are used to map soil characteristics like moisture content, temperature, nutrient content, etc. On the other hand, near-infrared and short-wave infrared waves are used to detect the concentration of various nutrients in soil such as nitrogen, phosphorus, potassium, and other characteristics like moisture, pH, organic matter, etc. Furthermore, the mapping or imagery data generated via sensing or satellite techniques ensures a uniform study of soil types.

With a deep analysis of the data generated, accurate predictions can be made about the nutrient and other needs of soil for particular crop farming. Therefore, adequate fertilizer support can be provided without wasting any resources. Judicious use, based on soil data, will ensure optimal and sustainable utilization of soil resources. Using sensor technologies, secondary data can also be generated regarding the micronutrients available in the soil for various crops. Ultimately, based on the data generated and analyzed, VRA can be employed for nutrients like nitrogen, phosphorus, potassium, etc. This will lead to judicious resource usage and yield will be increased. Other accessory benefits include lesser GHG emissions and reduced leaching of agrochemicals in the groundwater. It will economize the farming process by reducing the cost of fertilizers. Precise land leveling, through appropriate technologies, also makes the use of fertilizers and irrigation water-efficient (Jat et al. 2005).

4.6.1.3 Nutrient Use Efficiency

Nutrient use efficiency is another important facet of PF. In conventional farming, intensive measures are recommended for different inputs such as fertilizers, pesticides, and other practices. These practices often lead to reduced profits, reduced nutrient use efficiency, and environmental degradation (Sapkota et al. 2014; Meena et al. 2016, 2017b, 2019). Around 185 million tonnes of fertilizers per annum are used in the agricultural field all over the world (Shannon et al. 2020). On one hand, nutrient deficiencies through inefficient fertilizer usage will hamper the overall produce; however, overuse of fertilizers has also been reported to hamper yields (Jangir et al. 2016; Varma et al. 2017; Sharma et al. 2019). It has also been reported that minimal fertilizer use, when managed properly, produces no adverse effect on crop yield (Good and Beatty 2011; Kakraliya et al. 2017a, b). They also reported an additional cost, called as environmental cost, incurred when fertilizers are used in excess, amounting approximately 44% of total value of additional N-fertilizer applied. In PF, different zones within an agricultural field are delineated and nutrients in terms of fertilizers and other inputs are applied based on site-specific nutrient needs. However, it needs ample understanding of the delineation process, site-specific status and needs, spatial and temporal variability within the field and crop, and ultimately the effect of these factors on final yield (Hedley 2015). According to Diacono et al. (2013), nitrogen-use efficiency gets increased by 368% in PF when compared to conventional farming. Furthermore, they reported 10–80% less N-fertilizer usage in PF *vis-à-vis* conventional farming and residual nitrogen levels drop by 30–50%. However, to ensure optimal nutrient use in PF, two things are needed, i.e., efficient decision support system and equipment(s) capable of variable application at different scales (Hedley 2015). This is mainly achieved by following the technique of VRA. The VRA thus suffices two important purposes regarding nutrient use efficiency under PF, i.e., ensuring proper nutrient supply in deficient areas (site-specific needs) and preventing wastage via leaching, excessive accumulation (Balafoutis et al. 2017). An additional benefit is from decreased pollutants being emitted into the environment (Auernhammer 2001). Variable-rate irrigation system minimizes nutrient and water losses (Perea et al. 2018).

4.6.1.4 Energy Use Efficiency

With improved techniques like controlled traffic farming (CTF) and machine guidance (MG), we can control the tractor passes only over certain areas and also prevent the overlapping passes (Holpp et al. 2013; Van Evert et al. 2017). This will lead to energy-efficient agriculture with less fuel and input needs, ultimately leading to profitable farming and lesser GHGs emissions. There is 5–10% increased efficiency in farm operations in PF, mainly due to less overlapping of operations (Diacono et al. 2013), which is mainly attributable to usage of GPS and associated sensing technologies (Hedley 2015). GPS systems are introduced on agricultural implements that help them in automated guidance which, in turn, increased accuracy and reliability of mapping and activities undertaken (Diacono et al. 2013).

4.6.2 Environmental Stability

Precision farming is considered as one of the potential mitigation steps to the threat of climate change and environmental degradation (Balafoutis et al. 2017). By using lesser agrochemicals than in conventional farming, resource input is minimized. Consequently, lesser leaching of chemicals happens in soil, run-off, and groundwater. Excess fertilizer usage has also been reported to affect the aquatic life forms by creating dead zones in coastal ecosystems (Good and Beatty 2011). Optimal application of fertilizers through VRA can help mitigate the issue of dead zones to considerable extent. Furthermore, optimizing water usage through variable-rate irrigation helps to reduce GHGs emissions derived from application of fertilizers into the atmosphere (Balafoutis et al. 2017). The GHGs emissions can further be reduced via PF by optimal utilization of pesticide only at needy zones. It will subsequently decrease the rate of pesticide production at the industry level. Furthermore, lowered pollution (air, water, and soil) status can have a significant effect on environmental stability and sustainability. Reduced leaching of runoff water containing agrochemical residues, reduced water usage and soil exploitation, and reduced GHGs emissions are some of the benefits of PF that help in overall environmental stability (Finger et al. 2019). With PF, the overlapping of farm operations is less likely which leads to lowered fuel consumption and lesser GHGs emissions into the atmosphere. Available literature reports decreased consumption and expenditure (5–25%) on fuels under PF (Shockley et al. 2011; Jensen et al. 2012). Sehy et al. (2003) reported a 34% reduction in emission of nitrogen oxides (a GHG) from maize farming when VRA was implemented. The variable rate nutrient application possesses the potential to reduce GHGs from agriculture, mainly through accurate nutrient management (Asgedom and Kebreab 2011). In nutshell, under PF, lesser footprints are made in the environment.

4.6.3 Economics of Using Precision Farming

It is really difficult to quantify the benefits and analyze the economics of PF (Ashworth et al. 2018; Addicott 2019). Mainly, the improvements come in terms of yield, optimal use of input resources, improved management, and others. However, economics depends on various factors including the size of the field, number and extent of technologies applied, variability in heterogeneous zones, price dynamics of input–output in the market, etc. Among 234 ventures of farming ventures studied in Brazil, Griffin and Lowenberg-DeBoer (2005) reported 68% of cases to show profitable improvement in yield. Similarly, PF aims to economize the use of irrigation water that eventually serves two main purposes, i.e., reduces the wastage of precious water resources and prevents soil salinization through adequate irrigation

(Shrivastava and Kumar 2015). Additional 10–20% savings have been reported when GPS, GIS, and sensor technologies are used together in PF (Hedley 2015).

4.7 Difficulties in Adopting Precision Farming

Precision farming promises various benefits to farmers under varied conditions. However, each technology comes with its own pros and cons and PF is no exception. The initial investment cost for PF may be high at times. However, with advancing times, the cost of technologies is gradually decreasing. With improved efficiency in farming, it will be overall profitable. Precision farming is hugely dependent on the existence of variability in the field/ farm. If no variability exists, conventional farming is best, effective, and the cheapest strategy to be followed. The variability needs to be non-random so that it can be accounted for. Random variability is not useful for application under PF. For incurring the initial cost on technologies for PF, farming land needs to be large enough to economize the operations. Sometimes mechanization for sensors and other technologies may generate extra GHGs emissions leading to increased carbon footprints into the atmosphere (Balafoutis et al. 2017). However, this is a rare case as PF generally helps decrease GHG emissions and carbon footprints in the atmosphere. Sometimes, farmers lack technical knowledge which hampers the progressive profitable farming enterprise. Some technologies in PF are dependent on internet and networking facilities. However, internet access is not universal and many villages still lack the networking facilities. Farmers, mainly in developing countries, belong to that section which has low literacy levels. It also hampers the progress of PF.

4.8 Conclusions

Precision farming is a promising enterprise that possesses the potential to maximize the output while trying to economize the input application. It also aims at ensuring sustainability in agriculture and environment. PF is dependent on data variability and its optimal capturing and evaluation. Decision support system in PF works on analysis of data with appropriate statistical tools and software. Big data is gaining significance in PF and can work wonders for successful and sustainable agriculture. PF is dependent on different technologies that make the PF enterprises accurate and efficient. Resource use efficiency is eye-catching and sure benefit of PF which has many facets. Nutrient-, soil-, water-, energy-use efficiencies are some of the significant facets of PF. Though some difficulties hamper the rapid adoption of PF in developing countries, the trend of PF is positive and is sure to gain much ground in the near future.

4.9 Future Perspectives

Farmers mainly keep a constant eye on final profits from agriculture. Making PF a attractive venture needs a farmer to perceive it as profitable or at least generate interest in final customers with regard to the final generated produce. Providing loans with lowered interest rates, subsidy support, other incentives, and technical assistance to farmers practicing PF may be given a thought, at least till they become self-sustainable. Advisories and awareness programs need to be conducted to make farmers aware of PF and its components in detail. Role of extension workers, mass media, and other avenues may be used to generate awareness among farmers regarding PF. For optimal diffusion of PF techniques, several factors including relative advantage as against conventional farming, complex and compatible nature of technologies, and others need to be taken into consideration (Pathak et al. 2019). Taxes may be collected on usage of agrochemicals while subsidies and tax waivers may be provided on technology usage under PF.

References

Adamchuk VI (2010) Precision agriculture: does it make sense? Better Crops 94(3):4–6

Addicott JE (2019) The precision farming revolution: global drivers of local agricultural methods. Springer, pp 69–126

Aggarwal S (2004). Principles of remote sensing. Satellite remote sensing and GIS applications in agricultural meteorology, vol 7, pp 23–38

Alberio C, Izquierdo NG, Aguirrezábal LA (2015) Sunflower crop physiology and agronomy. In: Sunflower. AOCS Press, Urbana, pp 53–91

Ali J (2013) Role of precision farming in sustainable development of hill agriculture. National Seminar on Technological Interventions for Sustainable Hill Development, At G.B. Pant University of Agriculture & Technology, Pantnagar, Uttarakhand, India

Allen RG, Willardson LS, Burt C, Clemmens AJ (2003) Water conservation questions and definitions from a hydrologic perspective. In: Proceedings of the IA International Irrigation Show 18, San Diego, CA, USA

Asgedom H, Kebreab E (2011) Beneficial management practices and mitigation of greenhouse gas emissions in the agriculture of the Canadian Prairie: a review. Agron Sustain Dev 31 (3):433–451

Ashworth AJ, Lindsay KR, Popp MP, Owens PR (2018) Economic and environmental impact assessment of tractor guidance technology. Agri Environ Lett 3(1):180038

Auernhammer H (2001) Precision farming—the environmental challenge. Comput Electron Agric 30(1–3):31–43

Bach H, Mauser W (2018) Sustainable agriculture and smart farming. In: Earth observation open science and innovation. Springer, Cham, pp. 261–269

Bajiya R, Lakhran H, Kumar S, Seema (2017) Biochar for enhancing agricultural sustainability under climate change. Int J Curr Microb Appl Sci 6(2):1876–1883

Bakhtiari AA, Hematian A (2013) Precision farming technology, opportunities and difficulty. Int Jo Sci Emerg Technol Latest Trends 5(1):1–4

Balafoutis A, Beck B, Fountas S, Vangeyte J, Wal TV, Soto I, Gómez-Barbero M, Barnes A, Eory V (2017) Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability 9(8):133

Banhazi TM, Babinszky L, Halas V, Tscharke M (2012) Precision livestock farming: precision feeding technologies and sustainable livestock production. Int J Agric Biol Eng 5(4):54–61

Bhan S, Behera UK (2014) Conservation agriculture in India–problems, prospects and policy issues. Int Soil Water Conserv Res 2(4):1–2

Bhattacharyya R, Ghosh BN, Mishra PK, Mandal B, Rao CS, Sarkar D, Das K, Anil KS, Lalitha M, Hati KM, Franzluebbers AJ (2015) Soil degradation in India: challenges and potential solutions. Sustainability 7(4):3528–3570

Bongiovanni R, Lowenberg-DeBoer J (2004) Precision agriculture and sustainability. Precis Agric 5(4):359–387

Boretti A, Rosa L (2019) Reassessing the projections of the World Water Development Report. NPJ Clean Water 2(1):1–6

Candiago S, Remondino F, De Giglio M, Dubbini M, Gattelli M (2015) Evaluating multispectral images and vegetation indices for precision farming applications from UAV images. Remote Sens 7(4):4026–4047

Corwin DL, Lesch SM (2005) Apparent soil electrical conductivity measurements in agriculture. Comput Electron Agric 46(1–3):11–43

Dahiya S, Kumar S, Kumar S, Khedwal RS, Dagar H, Chaudhary C, Ankush A (2018) Management practices for improving water use efficiency of crops for boosting crop production. In: Rao RK, Sharma PK, Raghuraman M, Singh JK (eds) Agricultural, Allied Sciences & Biotechnology for Sustainability of Agriculture, Nutrition & Food Security. Mahima Publications, pp 115–121. ISBN: 978-81-926935-8-3

Dammer KH, Adamek R (2012) Sensor-based insecticide spraying to control cereal aphids and preserve lady beetles. Agron J 104(6):1694–1701

de Wit CD (1992) Resource use efficiency in agriculture. Agric Syst 40(1–3):125–151

Diacono M, Rubino P, Montemurro F (2013) Precision nitrogen management of wheat. A review. Agron Sustain Develop 33(1):219–241

Dong W, Zhang X, Wang H, Dai X, Sun X, Qiu W, Yang F (2012) Effect of different fertilizer application on the soil fertility of paddy soils in red soil region of southern China. PLoS One 7 (9):e44504

Dornelas M, Magurran AE, Buckland ST, Chao A, Chazdon RL, Colwell RK, Curtis T, Gaston KJ, Gotelli NJ, Kosnik MA, McGill B (2013) Quantifying temporal change in biodiversity: challenges and opportunities. Proc R Soc B Biol Sci 280(1750):20121931

Erickson B, Fausti S, Clay D, Clay S (2018) Knowledge, skills, and abilities in the precision agriculture workforce: an industry survey. Nat Sci Educ 47(1):1–11

Evans RG, Sadler EJ (2008) Methods and technologies to improve efficiency of water use. Water Resour Res 44(7):W00E04. https://doi.org/10.1029/2007WR006200

Evans RG, LaRue J, Stone KC, King BA (2013) Adoption of site-specific variable rate sprinkler irrigation systems. Irrig Sci 31(4):871–887

Far ST, Rezaei-Moghaddam K (2018) Impacts of the precision agricultural technologies in Iran: an analysis hexperts' perception & their determinants. Inform Process Agric 5(1):173–184

Finger R, Swinton SM, El Benni N, Walter A (2019) Precision farming at the nexus of agricultural production and the environment. Ann Rev Resour Econ 11:313–335

Frost AR, Parsons DJ, Stacey KF, Robertson AP, Welch SK, Filmer D, Fothergill A (2003) Progress towards the development of an integrated management system for broiler chicken production. Comput Electron Agric 39(3):227–240

Garibaldi LA, Gemmill-Herren B, D'Annolfo R, Graeub BE, Cunningham SA, Breeze TD (2017) Farming approaches for greater biodiversity, livelihoods, and food security. Trends Ecol Evol 32(1):68–80

Gomiero T (2016) Soil degradation, land scarcity and food security: reviewing a complex challenge. Sustainability 8(3):281

Gomiero T (2019) Soil and crop management to save food and enhance food security. In: Saving food. Academic Press, pp 33–87

Good AG, Beatty PH (2011) Fertilizing nature: a tragedy of excess in the commons. PLoS Biol 9 (8):e1001124

Goulding K, Jarvis S, Whitmore A (2008) Optimizing nutrient management for farm systems. Philos Trans R Soc B Biol Sci 363(1491):667–680

Griffin TW, Lowenberg-DeBoer J (2005) Worldwide adoption and profitability of precision agriculture implications for Brazil. Revista de Politica Agricola 14(4):20–37

Gupta GS (2019) Land degradation and challenges of food security. Rev Eur Stud 11:63

Gupta A, Kumar A (2018) Climate resilient agro-technologies for enhanced crop and water productivity under water deficit agro-ecologies. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 339–356

Hackeloeer A, Klasing K, Krisp JM, Meng L (2014) Georeferencing: a review of methods and applications. Ann GIS 20(1):61–69

Harrington M (2016) A spatial decision support system to address precision agriculture adoption challenges. A dissertation submitted to the University of Dublin in partial fulfilment of the requirements for the degree of MSc in Management of Information Systems, pp 11–14

Hedley C (2015) The role of precision agriculture for improved nutrient management on farms. J Sci Food Agric 95(1):12–19

Holpp M, Kroulik M, Kviz Z, Anken T, Sauter M, Hensel O (2013) Large-scale field evaluation of driving performance and ergonomic effects of satellite-based guidance systems. Biosyst Eng 116(2):190–197

Jangir CK, Singh D, Kumar S (2016) Yield and economic response of biofertilizer and fertility levels on black gram (*Vigna mungo* L.). Prog Rese An Int J 11(Special-VIII):5252–5254

Jat ML, Sharma SK, Gupta RK, Sirohi K, Chandana P (2005) Laser land leveling: the precursor technology for resource conservation in irrigated eco-system of India. In: Abrol IP et al (eds) Conservation agriculture-status and prospects. CASA, New Delhi, pp 145–14s

Jenrich M (2011) Potential of precision conservation agriculture as a means of increasing productivity and incomes for smallholder farmers. J Soil Water Conserv 66(6):171A–174A

Jensen HG, Jacobsen LB, Pedersen SM, Tavella E (2012) Socioeconomic impact of widespread adoption of precision farming and controlled traffic systems in Denmark. Precis Agric 13 (6):661–677

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017aa) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in indo-Gangetic Plains of India. J Curr Microb Appl Scie 6(3):152–163

Kakraliya SK, Kumar N, Dahiya S, Kumar S, Yadav DD, Singh M (2017bb) Effect of integrated nutrient management on growth dynamics and productivity trend of wheat (*Triticum aestivum* L.) under irrigated cropping system. J Plant Dev Sci 9(1):11–15

Kakraliya SK, Kumar S, Kakraliya SS, Choudhary KK, Singh LK (2018) Remedial options for the sustainability of rice-wheat cropping system. J Pharmacogn Phytochem 7(2):163–171

Kempenaar C, Been T, Booij J, Van Evert F, Michielsen JM, Kocks C (2017) Advances in variable rate technology application in potato in The Netherlands. Potato Res 60(3–4):295–305

Kitchen NR, Clay SA (2018) Understanding and identifying variability. Precis Agric Basics 11:13–24

Krishna KR (2019) Introduction to unmanned aerial vehicle systems utilized in agriculture. In: Unmanned aerial vehicle systems in crop production: a compendium. CRC Press, Boca Raton, FL

Kumar S, Sheoran S, Kakraliya SK, Kumar P, Meena RS (2016) Drought: a challenge for Indian farmers in context to climate change and variability. Prog Rese An Int J 11(Special-IX):6243–6246

Kumar S, Karaliya SK, Chaudhary S (2017) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. Int J Curr Microbiol App Sci 6 (3):142–151

Kumar S, Karaliya SK, Chaudhary S (2017a) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. J Curr Microb Appl Sci 6 (3):142–151

Kumar S, Meena RS, Yadav GS, Pandey A (2017b) Response of sesame (*Sesamum indicum* L.) to Sulphur and lime application under soil acidity. Int J Plant Soil Sci 14(4):1–9

Kumar S, Meena RS, Pandey A, Seema (2017c) Soil acidity management and an economics response of lime and sulfur on sesame in an alley cropping system. Int J Curr Microb Appl Sci 6(3):2566–2573

Kumar S, Meena RS, Jakhar SR, Jangir CK, Gupta A, Meena BL (2019) Adaptation strategies for enhancing agricultural and environmental sustainability under current climate. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 226–274

Lakhran H, Kumar S, Bajiya R (2017) Crop diversification: an option for climate change resilience. Trends Biosci 10(2):516–518

Levidow L, Zaccaria D, Maia R, Vivas E, Todorovic M, Scardigno A (2014) Improving water-efficient irrigation: prospects and difficulties of innovative practices. Agric Water Manag 146:84–94

Lindblom J, Lundström C, Ljung M, Jonsson A (2017) Promoting sustainable intensification in precision agriculture: review of decision support systems development and strategies. Precis Agric 18(3):309–331

Maslaris N, Tsialtas IT, Ouzounidis T (2010) Soil factors affecting yield, quality, and response to nitrogen of sugar beets grown on light-textured soils in northern Greece. Commun Soil Sci Plant Anal 41(13):1551–1564

Mayberry D, Ash A, Prestwidge D, Godde CM, Henderson B, Duncan A, Blummel M, Reddy YR, Herrero M (2017) Yield gap analyses to estimate attainable bovine milk yields and evaluate options to increase production in Ethiopia and India. Agric Syst 155:43–51

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena RS, Gogoi N, Kumar S (2017a) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359

Meena RS, Kumar S, Pandey A (2017b) Response of sulfur and lime levels on productivity, nutrient content and uptake of sesame under guava (*Psidium guajava* L.) based agri-horti system in an acidic soil of eastern Uttar Pradesh, India. J Crop Weed 13(2):222–227

Meena RS, Kumar V, Yadav GS, Mitran T (2018) Response and interactionof *Bradyrhizobium japonicum* and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Kumar S, Bohra JS, Lal R, Yadav GS, Pandey A (2019) Response of alley cropping-grown sesame to lime and Sulphur on yield and available nutrient status in an acidic soil of Eastern India. Energ Ecol Environ 4:65–74. https://doi.org/10.1007/s40974-019-00113-w

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depthand amendments on soil physical and hydrological properties of anAlfisol in Central Ohio, USA. Geoderma 363:1141164

Mgbemene CA, Nnaji CC, Nwozor C (2016) Industrialization and its backlash: focus on climate change and its consequences. J Environ Sci Technol 9(4):301–316

Mondal P, Basu M (2009) Adoption of precision agriculture technologies in India and in some developing countries: scope, present status and strategies. Prog Nat Sci 19(6):659–666

Mountrakis G, Im J, Ogole C (2011) Support vector machines in remote sensing: a review. ISPRS J Photogramm Remote Sens 66(3):247–259

Mythili G, Goedecke J (2016) Economics of land degradation in India. In: Economics of land degradation and improvement–a global assessment for sustainable development 2016. Springer, Cham, pp 431–469

Naresh RK, Singh SP, Misra AK, Tomar SS, Kumar P, Kumar V, Kumar S (2014) Evaluation of the laser leveled land leveling technology on crop yield and water use productivity in Western Uttar Pradesh. Afr J Agric Res 9(4):473–478

Nath R, Luan Y, Yang W, Yang C, Chen W, Li Q, Cui X (2015) Changes in arable land demand for food in India and China: a potential threat to food security. Sustainability 7(5):5371–5397

Neupane J, Guo W (2019) Agronomic basis and strategies for precision water management: a review. Agronomy 9(2):87

Oliver MA (2013) Precision agriculture and geostatistics: how to manage agriculture more exactly. Significance 10(2):17–22

Ozturk O, Topal A, Akınerdem F, Akgün N (2008) Effects of sowing and harvesting dates on yield and some quality characteristics of crops in sugar beet/cereal rotation system. J Sci Food Agric 88(1):141–150

Panayi E, Peters GW, Kyriakides G (2017) Statistical modelling for precision agriculture: a case study in optimal environmental schedules for Agaricus Bisporus production via variable domain functional regression. PLoS One 12(9):e0181921

Pathak HS, Brown P, Best T (2019) A systematic literature review of the factors affecting the precision agriculture adoption process. Precis Agric 20(6):1292–1316

Pedersen SM, Lind KM (2017) Precision agriculture–from mapping to site-specific application. In: Precision agriculture: technology and economic perspectives. Springer, Cham, pp 1–20

Peerzado MB, Magsi H, Sheikh MJ (2019) Land use conflicts and urban sprawl: conversion of agriculture lands into urbanization in Hyderabad, Pakistan. J Saudi Soc Agric Sci 18 (4):423–428

Perea RG, Daccache A, Díaz JR, Poyato EC, Knox JW (2018) Modelling impacts of precision irrigation on crop yield and in-field water management. Precis Agric 19(3):497–512

Pingali PL (2012) Green revolution: impacts, limits, and the path ahead. Proc Natl Acad Sci 109 (31):12302–12308

Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot 114 (8):1571–1596

Rauw WM, Gomez-Raya L (2015) Genotype by environment interaction and breeding for robustness in livestock. Front Genet 6:310

Rees RM, Griffiths BS, McVittie A (2017) Sustainable intensification of agriculture: impacts on sustainable soil management. In: International yearbook of soil law and policy. Springer, Cham, pp 7–16

Reynolds TW, Waddington SR, Anderson CL, Chew A, True Z, Cullen A (2015) Environmental impacts and constraints associated with the production of major food crops in sub-Saharan Africa and South Asia. Food Secur 7(4):795–822

Sadler EJ, Evans R, Stone KC, Camp CR (2005) Opportunities for conservation with precision irrigation. J Soil Water Conserv 60(6):371–378

Sapkota TB, Majumdar K, Jat ML, Kumar A, Bishnoi DK, McDonald AJ, Pampolino M (2014) Precision nutrient management in conservation agriculture based wheat production of North-west India: profitability, nutrient use efficiency and environmental footprint. Field Crop Res 155:233–244

Sebby K (2010) The green revolution of the 1960's and its impact on small farmers in India. Environmental Studies Undergraduate Student Theses. 10. https://digitalcommons.unl.edu/envstudtheses/10

Sehy U, Ruser R, Munch JC (2003) Nitrous oxide fluxes from maize fields: relationship to yield, site-specific fertilization, and soil conditions. Agric Ecosyst Environ 99(1–3):97–111

Shafi U, Mumtaz R, García-Nieto J, Hassan SA, Zaidi SA, Iqbal N (2019) Precision agriculture techniques and practices: from considerations to applications. Sensors 19(17):3796

Shah F, Wu W (2019) Soil and crop management strategies to ensure higher crop productivity within sustainable environments. Sustainability 11(5):1485

Shannon DK, Clay DE, Kitchen NR (2020) Precision agriculture basics. Wiley, p 5

Shanwad UK, Patil VC, Dasog GS, Mansur CP, Shashidhar KC (2002) Global positioning system (GPS) in precision agriculture. In: The Asian GPS conference 2002 October, pp 24–25

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019) Growth, yield and quality of cluster bean (*Cyamopsis tetragonoloba*) as influenced by integrated nutrient management under alley cropping system. Indian J Agric Sci 89(11):1876–1880

Shibusawa S, Haché C (2009) Data collection and analysis methods for data from field experiments. Syst Analy Model Food Agric 12:311

Shockley JM, Dillon CR, Stombaugh TS (2011) A whole farm analysis of the influence of auto-steer navigation on net returns, risk, and production practices. J Agric Appl Econ 43(1):57–75

Shrivastava P, Kumar R (2015) Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi J Biol Sci 22(2):123–131

Singh AK (2010) Precision farming. Water Technology Centre, IARI, New Delhi

Sood K, Singh S, Rana RS, Rana A, Kalia V, Kaushal A (2015) Application of GIS in precision agriculture. In: Paper presented as lead lecture in national seminar on "Precision farming technologies for high Himalayas, pp 04–05

Struik PC, Kuyper TW (2017) Sustainable intensification in agriculture: the richer shade of green. A review. Agron Sustain Dev 37(5):39

Tantalaki N, Souravlas S, Roumeliotis M (2019) Data-driven decision making in precision agriculture: the rise of big data in agricultural systems. J Agric Food Inform 20(4):344–380

Thornton PK (2010) Livestock production: recent trends, future prospects. Philos Trans R Soc B Biol Sci 365(1554):2853–2867

UN Educational, Scientific, and Cultural Organization (2006) Water, a shared responsibility, Rep. 2, World Water Assessment Programme, Berghahn, New York

Van Evert FK, Gaitán-Cremaschi D, Fountas S, Kempenaar C (2017) Can precision agriculture increase the profitability and sustainability of the production of potatoes and olives? Sustainability 9(10):1863

Van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z (2013) Yield gap analysis with local to global relevance—a review. Field Crop Res 143:4–17

Van Loon J, Speratti AB, Gabarra L, Govaerts B (2018) Precision for smallholder farmers: a small-scale-tailored variable rate fertilizer application kit. Agriculture 8(4):48

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan region, India. Int J Chem Stud 5(4):1558–1560

Vollrath D (2007) Land distribution and international agricultural productivity. Am J Agric Econ 89 (1):202–216

West GH, Kovacs K (2017) Addressing groundwater declines with precision agriculture: an economic comparison of monitoring methods for variable-rate irrigation. Water 9(1):28

Wolfert S, Ge L, Verdouw C, Bogaardt MJ (2017) Big data in smart farming–a review. Agric Syst 153:69–80

Yousefi MR, Razdari AM (2015) Application of GIS and GPS in precision agriculture (a review). Int J Adv Biol Biomed Res 3(1):7–9

Nanomaterials for Agriculture Input Use Efficiency

5

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Abstract

Nanotechnology is an interdisciplinary stream of science which deals with the synthesis and application of nanoparticles (NPs) ranging from 1 to 100 nm. Nanotechnology is seen as a new tool for the various problems faced in agriculture and other allied sectors. Agriculture system is facing problems like generation of resistance among microbes due to excessive use of pesticides and deteriorating soil health by the abundant use of fertilizers, exhibiting damaging effect on the environment. A large quantum of applied fertilizers and pesticides get lost in the surrounding and not consumed by plants which limit the use of conventional methods. Nanoscience could be the potential solution to these limitations because bioactive compounds are encapsulated here and release at a controlled rate, providing input use efficiency. Diseases could be easily detected by the use of nanosensors at an early stage and thus also be controlled at the earliest for better productivity. Various disease controlling products are in use, such as nano-pesticides, nano-fungicides and nano-bactericides, to protect the crops from various kinds of biological stresses caused by different microorganisms. Small surface area to volume ratio of NPs contributes to their better absorption ability. Post-harvest techniques using nanosensors help check food quality with better packaging and transport which results in reduced post-harvest losses. The agriculture sector also contributes to a large amount of agriculture waste which is being transformed using nanomaterials and put into efficient use. Productivity in agriculture has been improved using nanobiotechnology by the use of nanocarriers to transfer the DNA (deoxyribonucleic acid) fragment at the proper site and to bring the desired result. Thus, nanomaterials contribute to improved nutrients use efficiency. This chapter entails the use of nanomaterials in improving soil health, plant productivity, disease detection, control and treatment, genetic transformation, post-harvest value addition, and reducing agriculture waste. Along with these benefits, nanomaterials may cause harm to the environment, so proper hazard assessment and regulations should be brought in for the optimal use of nanotechnology. Use of nanomaterials can result in the achievement of sustainable agriculture, thus, could be promoted with proper regulation in place.

Keywords

Agriculture · Input use efficiency · Nanoparticles · Nanosensors · Nanotechnology

Abbreviations

Ag	Silver
Au	Gold
CaO	Calcium oxide
CO_2	Carbon dioxide
Cu	Copper

DNA	Deoxyribonucleic acid
Fe	Iron
FeO	Iron oxide
Gt	Gigatons
LDH	Layered double hydroxide
MgO	Magnesium oxide
MWCNTs	Multi-walled carbon nanotubes
NBS	Nano-biosensor
Ni	Nickel
nm	Nanometer
NPs	Nanoparticles
QDs	Quantum dots
RNA	Ribonucleic acid
ROS	Reactive oxygen species
RUE	Resource use efficiency
Si	Silicon
SiO_2	Silicon dioxide
SWCNTs	Single-walled carbon nanotubes
TiO_2	Titanium dioxide
Zn	Zinc
ZnO	Zinc oxide

5.1 Introduction

Agriculture is the chief occupation of India and other developing and least developed countries; it employs 70% of the population (Kumar et al. 2017a, b, c; Kakraliya et al. 2018a; Gupta and Kumar 2018). The modern agriculture heavily depends on the use of chemical fertilization and pesticidal application to promote and ensure a better and healthy plant growth and therefore crop yield (Meena et al. 2016a, b). About 40–60% of plant growth is directly related to fertilizers applied; thus, fertilizers and agrochemicals play a key role in the growth of crops (Roberts 2009). Among agrochemicals pesticides are crucial for plant health as 20–40% of the crop is damaged by pest incidence which accounts for US$ 42.66 million of crop loss per year (Sushil 2016). But 90% of this poured pesticide is not used by the plant and contributes to poor crop health, the emergence of resistance in pests, hazardous chemicals bioaccumulation, and climate change (Stephenson 2003; Ghormade et al. 2011; Meena et al. 2020b). Indiscriminate and unnecessary use of chemicals in agriculture had created severe consequences in soil and agroecosystem with reduced crop yield (Meena et al. 2020a). Due to the huge population size, there is a need to increase crop productivity to end hunger and malnutrition (Jangir et al. 2017; Meena et al. 2018a). Sustainable livelihood could be ensured by achieving food sufficiency (Layek et al. 2018). These could be solved by adopting nano-techniques and nanomaterials for early detection of diseases using plant material in a small amount, with a fast response at lesser cost and with reliable results. Table 5.1 shows the

Table 5.1 Various nanotechnology derived products having potential applications in farming

Nanocomposites	Uses	References
Biodegradable thermoplastic starch (TPS)	Reduced water permeability and improved tensile strength	Park et al. (2002)
Nanosensors	Liposome encapsulated nano-biosensor shown pesticide presence	Vamvakaki and Chaniotakis (2007)
Nano formulations of sodium alginate or hydrolyzed collagen	Preservation of loquat and cherry	Jia et al. (2008)
Primo MAXX	Grass growth regulatory	Prasad et al. (2014)
Nanoemulsion	Nanoemulsion derived from neem oil exhibited larvae killing properties	Anjali et al. (2012)
Nano-clays and zeolites nanoparticles (NPs)	Exhibited better water retention capacity and restricted liberation of agrochemicals, resulting in improved intake by crops	(http://www.geohumus.com)
Acetamiprid laden nano capsules of alginate-chitosan	Improved efficiency and better agrochemical delivery to crop plants	Kumar et al. (2015)
Zinc oxide (ZnO) and titanium dioxide (TiO_2) as nano-nutrients	Enhanced growth and antioxidants in tomatoes (*Lycopersicon esculentum*)	Raliya et al. (2015)

different nanomaterials and nanocomposites having applications in improving agricultural input use efficiency. Nanotechnology could be an efficient tool to achieve food sufficiency. Currently, nanotechnology is used in the assembly of nano-pesticides and nano-fertilizers through delayed absorption properties and improved efficiency to increase crop productivity. They give result at a lower dose compared to conventional pesticides. The nano-based detection kits are good both in speed and power of detection (Prasanna 2007).

In the agriculture sector, nanoscience exploration and development could be used for bringing new development in the production of a genetically modified organism, improved animal breed, precision farming, nanosensors for disease detection, food quality maintenance, and agriculture waste management. Use of nanotechnology in agriculture will go from the farming inputs improvement to formation of novel functional materials, techniques, and instrumentation designing for food safety (Joseph and Morrison 2006). It will have a high impact on society as a whole, but concerns regarding the unfavorable effect of NPs on the surrounding environment, human beings, and marine life will be there with the increased use of nanotechnology. Current developments in chemistry and physical science have created expertise for nanoscience technology, having great application in the agriculture sector. Due to changing weather patterns, new problems are faced in this sector such as rising demand for safe and healthy foodstuff, higher risk of disease infection, and farming productivity loss risk (Hager 2011).

5.2 Nanobiotechnology

It is the technology that uses nanoscale carriers to transfer chemical and DNA (deoxyribonucleic acid) to the target site and is the fusion of nanotechnology and biotechnology. Nanobiotechnology has applications in food, agriculture, and energy sectors. Nanobiotechnology gave application with innovative tools to change the genetic constitution and even manufacture organisms with good and desirable traits as shown in Fig. 5.1. Nanostructures, including nanofibers, NPs, and nanocapsules area unit accustomed transmit foreign genes and chemicals that transform genes (Torney et al. 2007). Cellular "injection" to genetically modified golden rice (*Oryza sativa*) has been performed for the effieint use of carbon nanofibers containing foreign DNA (AZoNano.com 2003). Engineering has the potential of enhancing agriculture output through genome improvement in crops and animals in conjunction with the deliverance of DNA and chemical drugs to particular places in floral and faunal structures (Kuzma 2007; Maysinger 2007).

Nanobiotechnology offers a tool to generate insect-resistant novel crop varieties by transferring specific insect resistance gene to the targeted site. Other methods to transfer DNA are DNA-coated nanostructures which are worn as a shot in gene-gun bombardment tools for transformation of plants to transmit the preferred genes to the objected crop plants (Lyons 2010; Vijayakumar et al. 2010). Chitosan NPs coated small interfering ribonucleic acid (RNA) delivery vehicles are an efficient system to change the gene regulation and provide an excellent option to transfer RNA because small interfering RNA binds strongly with the chitosan bioconjugate (Zhang et al. 2010). To edit the genome of plants and make CRISPR/Cas9 technique more useful, NPs based CRISPR/Cas9 having single guide RNA were made for efficient gene

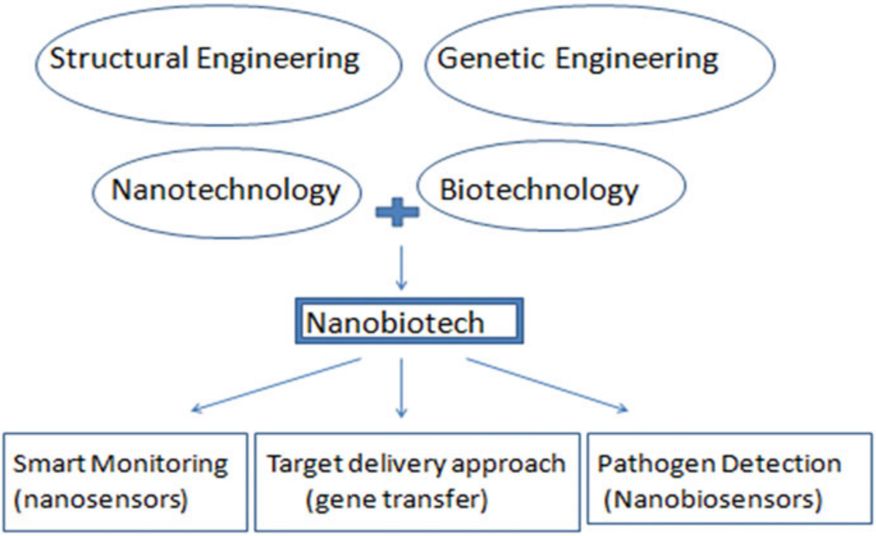


Fig. 5.1 Different applications of nanobiotechnology

delivery. These methods will improve the effectiveness and fidelity of CRISPR/Cas gene-editing systems. For instance, approximately 30% higher success rate of genome editing to cytoplasmic or nuclear genome was achieved when editing was performed using anionic arginine gold (Au) NPs having Cas9En (E-tag)-ribonucleoprotein with single guide RNA. This technique would majorly facilitate further research activities in crop development.

A mixture of nanomaterials, generally carbon derived nanomaterials increased the growth and development, total biomass, root and shoot length of seedlings and germination percentage in crops *viz.* tomato, corn (*Zea mays*), wheat (*Triticum aestivum*), lettuce (*Lactuca sativa*), onion (*Allium cepa*), radish (*Raphanus sativus*), pumpkin (*Cucurbita pepo*), ryegrass (*Lolium perenne*), and rape (*Brassica* spp.) (Agrawal and Rathore 2014). Nanomaterials application also has an impact on the physiological determinants, for example, enhanced nitrogen assimilation and photosynthetic rate in a handful of crops, in soybean (*Glycine max*) (Agrawal and Rathore 2014), spinach (*Spinacia oleracea*) (Liu et al. 2010), and peanut (*Arachis hypogaea*) crop (Giraldo et al. 2014a, b). Photosynthetic rate thrice time enhancement has been reported by the application of single-walled carbon nanotubes (SWCNTs) containing cerium NPs which took the passive route and once and for all place in the lipid bilayer of chloroplast in comparison to that of control plant and showed highest electron transfer rates (Giraldo et al. 2014a, b).

Nanobiotechnology considered as a useful tool and technique for improving the plant productivity by changing gene expression and targeting a specific gene with a particular drug. Other such examples stated by Lei et al. (2008) observed the reduced oxidative tension in spinach chloroplast by nano TiO_2 application under ultraviolet-B radiation. Moreover, similarly within rice reduced oxidative stress because of the intergenerational transfer of fullerol via seeds (Lin et al. 2009). Increased chlorophyll-a level in maize was observed by using tetramethyl ammonium hydroxide coated magnetic NPs (Racuciu and Creanga 2006) on tomato. Multi-walled carbon nanotubes (MWCNTs) applications caused alteration in gene expression in crop plants and cell lines. Nano-iron oxide (FeO) resulted in agronomic traits change by increased foliage and pod dry weight as well as grain production exposure in soybean crop (Sheykhbaglou et al. 2010). In pumpkin, increased root elongation was observed by the use of FeO which resulted in solubilization of iron (Fe) (Wang et al. 2011). Other applications of nanobiotechnology include the development of biosensors, which reduces the cost, time of detection, and efforts and improves the efficiency and productivity of the agriculture system. Biosensors found their use in detecting a nutrient deficiency, to calculate and monitor crop development and soil health situation, lethality, admission of agrochemicals and pesticides to the surrounding environment and diseases (Cheng et al. 2016). Naturally, this is measured by the biological system, but the fusion of biology and nanosystems in nanosensors improves the sensitivity, specificity, and rapid responses to sense the defects (Dubey and Mailapalli 2016). It could be used to improve water use efficiency via automation of watering using biosensors.

Similarly, quick and accurate sensing of pathogens and insects would assist in the timely appliance of fertilizers and pesticides in defending the crop plants from insect and pest attack. Afsharinejad et al. (2016) prepared a wireless nanosensor used for sensing the insect infestation. This nano-biosensor (NBS) senses the different released volatile organic compounds in several host plant species regarding the insect and pests' variants. Singh et al. (2010) observed that Au NPs derived immune sensor is successful in detecting Karnal bunt syndrome in wheat crop. In addition to this, nano-bionics is the emerging tool in which NPs are incorporated in the tissues and plastids of living crop plants designed for imaging and sensing objects in plants surrounding areas and for transferring signal as infrared rays or yet self-powering of crop plants at the same time as a light producer have immense use in precision farming (Kwak et al. 2017). Giraldo et al. (2014a, b) stated the augmented electron transfer pace of light-treated plastids by 49% under in natural biological situations via incorporation of SWCNTs by fulfilling light absorption. It was also stated that SWCNTs augmented the light-absorbing ability near-infrared spectrum through reducing the production of reactive oxygen species (ROS) within the plastid and can manipulate the signal getting the course in crops, and this boosted the photosynthetic rate and productivity of crops. Plants respond to biotic and biotic stress through different means such as the production of salicylic acid, methyl jasmonate, and jasmonic acid. These could be detected at an early level by use of nanosensors and could provide a solution at an early stage. Wang et al. (2010) developed the nanosensor for sensing the level of salicylic acid within oilseed during pathogenic fungus infestation by using a tailored gold electrode NBS in the company of copper (Cu) NPs. So, we observed different application of nanosensors in crop management, and it opens a new window for further research.

5.3 Nanotechnology for Improving Crop Productivity

Crop productivity is explained as the comparative relation of crop output to crop input. By increased use of resources, productivity could be enhanced. This will increase the farmer's income and make agriculture a profitable sector. For resource use efficiency (RUE), one of the highly targeted fields is improving crop yield. It was achieved in the past using plant breeding methods, fertilizers use, and plant protection products. It could also be achieved using a smart delivery system. Smart delivery systems are the delivery of bioactive molecules or essential nutrients or any pesticide molecule in a controlled way (Kashyap et al. 2015). The smart delivery system is the collective term for pre-programmed, remotely regulated, spatially targeted, timely controlled, self-regulated, and multifunctional characteristics for resource use. However, now these technologies are not so effective in improving yield, so new technologies like genetic engineering, nanoscience, etc., will be the focus to improve productivity. Various levels in productivity enhancement starting from higher absorption of sunlight to the higher activity of rubisco, to increased electron transport rates in photosystem, enhanced water activity, and transpiration rates could be targeted using these technologies. Plants transform the radiant energy of the sun to the chemical potential through photosynthesis, which is preserved in the form of glucose in plants, so this process can be used in plant engineering (Sage et al.

2012). Engineering of C_3 (plants in which the primary carbon dioxide (CO_2) acceptor is 3-carbon compound) plants to use the C_4 (plants in which the primary CO_2 acceptor is 4-carbon compound) pathway would be used to enhance photosynthesis efficiency as C_4 shows better photosynthetic efficiency even at a higher temperature (Rizal et al. 2012).

Nanoscience is one of the emerging technologies, which could be used to improve photosynthetic efficiency. Work is going on in this field; earlier literature is not enough regarding the use of nanotechnology for increasing photosynthetic rate. The relationship between improved photosynthesis and nanomaterial use has been reported. The titanium oxides NPs application showed the improved photosynthetic rate, which is attributed by high light absorption by leaves of the plant due to the extensive photocatalytic activity of anatase crystal nTiO2, here NPs protect the chloroplast from aging, hence advances the photosynthetic rate of plants (Hong et al. 2005). The enhanced rubisco activation rate, in turn, increases the crop productivity (Ma et al. 2008; Gao et al. 2008). It also increases transpiration and leaf water conductance (Lei et al. 2007). Recently, a new technology known as “Nano-bionics” has been emphasized, which adds nanomaterials to living plants and changes their original function (Scholes and Sargent 2014). Here the artificial photosynthetic system is being designed and developed to strengthen faster developments of plants which would be a new source of clean and green energy. It could be used to enhance the recovery rate from photoinhibition. For the first time, the use of nano-bionics in crop science was reported by a faction of researcher belonging to The Massachusetts Institute of Technology Researchers used the SWCNTs suspension on the foliar part of *Arabidopsis thaliana* as well as on the chloroplast isolated from *Spinacia oleracea* foliar portion. SWCNTs treatment improved the transportation rate of the electron, which is due to the high electrical conductance, helps in higher absorbance of the light spectrum, which is usually less absorbed. This higher light absorption is mainly because of increased absorption in the ultraviolet (UV) and near-infrared range. The shelf life of chloroplast also improved by 2 h upon nano-suspension application (Giraldo et al. 2014a, b). Plant photosynthetic activity increased thrice compared to controls and increased electron transport rate has been observed. So, the use of nano-bionics in agriculture productivity enhancement could be used, and this experiment established the relationship between increased plant productivity and nano-bionics use. This way, nano-bionics is a new tool to boost the photosynthetic rate and to improve the sunlight use and efficiency of CO_2 fixation with increased carbohydrate synthesis.

5.4 Nanotechnology for Soil Management

Fertilizers are the chemical materials used to supply essential nutrients to the soil, and in turn, to plants to beat nutrient deficiency and to protect the plant from adverse impact because of nutrients deficiency (Kakraliya et al. 2017a, b, 2018b; Sharma et al. 2019). Higher use of fertilizers costing more to the farmers and also harming the environment and deteriorating soil health (Meena et al. 2018). Nano-fertilizers

Table 5.2 Various nano-fertilizers and their response against different pathogens

Type	Nano-fertilizers	Antimicrobial response of nano-fertilizers to plant pathogens	References
Plant development supporting microorganisms	Ag (silver)	*Bacillus cereus*	Sunkar and Valli Nachiyar (2012)
	Ag	*Fusarium oxysporum*	Ahmad et al. (2003)
	Ag	*Escherichia coli,* and *Streptococcus thermophilus*	El-Shanshoury et al. (2011)
	Ag and TiO_2	*Lactobacillus strains*	Jha and Prasad (2010)
	Ag	*Corynebacterium* sp.	Zhang et al. (2005)
	Au	*Klebsiella pneumoniae*	Malarkodi et al. (2013)

could be a new alternative to these problems. Nano-fertilizers consist of the NPs, which supply nutrients to rhizosphere in required quantity and at the required time (Subramanian and Tarafdar 2011; Yadav et al. 2020). Various NPs being used in nano-fertilizers manufacturing with antimicrobial activity are shown in Table 5.2. Nonfertilizer could be prepared by accumulating fertilizer in porous nanocapsule, in a polymer coat, or as a nanoemulsion, which supplies nutrients to plant more efficiently compared to regular fertilizers. Combining nanodevices with the nano-fertilizers mediates its controlled release into the environment, and thus protects the environment, which ensures better RUE. In total, it improves productivity, RUE, and saves the environment from excessive fertilizer use. This technology conserves the soil health more economically, as it is required in a lesser amount for the same effect in comparison to traditional fertilizers. Nano-fertilizers possess some specific properties which make it more useful in agriculture for improved use efficiency:

1. The higher surface area of nano-fertilizers makes its greater availability to the metabolic processes resulting in higher productivity with a lesser amount of fertilizers.
2. Nano-fertilizers provide higher nutrient use efficiency and improved nutrient uptake facilitated by more significant surface area in addition to smaller particle size than leaf and root pore.
3. They have higher penetration ability for plants attributed by their small particle size (less than 100 nm—nanometer).
4. They have varying solubility in different kind of solvents.
5. Nanoparticles have increased the specific surface area and higher amount per unit area of fertilizers which enhances their penetration and uptake ability.
6. Nanoencapsulated fertilizers increase its availability to plants.

Table 5.3 Commercially using nano-fertilizers

Commercial nano-fertilizers	Constituents
Biozar Nano-fertilizer	Macromolecules, organic substances, and micronutrients mixture
Master Nano chitosan organic fertilizer	A mixture of chitosan, phenolic constituents, salicylic acids, and organic acid
Nano max NPK fertilizer	Combination of vitamins, organic carbon, different organic acids, amino acids, organic micronutrients, and probiotic
TAG NANO fertilizers	Protein, lactose and gluconate complexed with humic acid, vitamins, probiotics, micronutrients, and fractionate of seaweeds
Nano-GroTM	Immunity booster and plant hormones
Nano-Ag answer ^{R}	Mineral electrolyte, microorganism, and sea kelp
Nano green	Extracted components of palm, soybeans, corn, grain, coconut (*Cocos nucifera*), and potatoes (*Solanum tuberosum*)

These features make nano-fertilizer a better alternative to fertilizers with better efficiency. Nonfertilizer releases nutrients into the soil at the controlled rate, which is maintained by either mixing the nano-fertilizers with different materials, for example, special biofilms, hydrogels, or by additional biopolymers, for instance, chitosan to minimize the uncontrolled release in the surrounding soil material (Kashyap et al. 2015). These different materials bind with the fertilizers and form complexes by attaching with different mineral NPs abstracted from the soil constituents or different kind of ceramic resources (Choy et al. 2007), which were applied in making restricted release pots, blocks, or film. Nonfertilizers are used according to different environmental conditions such as irradiance or limiting concentration of essential element such as Cu, Fe and nickle (Ni) in the soil, controlled release of nanofertilizers make their effecient use as per required conditions. For this purpose, the encapsulated organic NPs or emulsions can be useful.

Nano-fertilizers commonly showtheir presence in the market, but in agriculture its use is not much explored. Companies in this field are still working to come up with the best fertilizer product. Many commercial nano-fertilizers are now present in the market, which are mentioned in Table 5.3 along with their respective constitutes. These are also specified in release rates, their uptake by plants and their biological fate, which ultimately improves the efficiency of plants in nutrient absorption. Previously used methods of spraying and sprinkling were only partly absorbed by plants, which could be overcome with nano-fertilizer's use. Many nano-sized fertilizers are available commercially, which are characterized by their biocompatibility and unique optical properties. They have several advantages of being quick, sensitive, and flexible (Thakur et al. 2018).

Nano-fertilizers are having nano sizes, mainly differ from the conventional fertilizers used in agriculture. These changes include the change in the quantum size consequence, ions distribution, and physiochemical characteristics of substances (Nair et al. 2010). In these situations, results are entirely dependent on the use of the semiconductor in the formation of NPs. Kandasamy and Prema (2015) reported improved transduction properties for nano-fertilizers, endorsed by outsized surface area to volume proportion of prepared nanocomposites and this found use in the analysis of agriculture products. Use of nanoscale particles for biological examination determining the activity or presence of chosen compounds become further flexible, quicker, and more perceptive (Kandasamy and Prema 2015; Meena et al. 2019). Therefore, these found great application with improved results in agriculture for improved nutrient use efficiency. Application of different nano-fertilizers has a crucial function in reducing the pollution, negative affect environment, enhancing crop yield, and reducing the fertilization cost for crop production. Hence, the efficiency of nutrient use could be improved with efficient use of nano-fertilizers in the crop fields. The nano-fertilizers improved yield and crop growth when applied at optimum concentrations and doses.

5.5 Nanotechnology for Plant Disease Control

5.5.1 Plant Disease Detection

Another challenge being faced in agriculture is the higher incidence of pathogen attack due to a changing climate, and this encounters food security worldwide. The increasing population will further need more food or higher food productivity to cater the demand. So, there will be higher food demand; climate change has created a daunting challenge for plant pathologists. Nanotechnology is providing new opportunities for these challenges. It has been recognized as a critical technology among six technologies by European commission which provides sustainable growth in industrial application. Nanoparticles are produced both naturally and engineered. Natural NPs like oceanic salt, volcanic dust, and viral particles present naturally, but these are irregular in size (Hochella et al. 2015). Engineered NPs synthesized are uniform in size and work more effectively than natural ones. These could be spherical, sheets, rods, multi-walled tubes, or dendritic in shape. On account of NPs, greater surface area to volume proportion, they act as an efficient carrier of varied drugs and chemicals. Use of the nanoscience for the detection of disease at an early stage of infestation could prevent tremendous food loss. These methods are humbler, sensitive, and more effective in disease detection. A real-time detector of crop infestation could prove useful for the farming community. A combination of nanotechnology and biotechnology in sensors will form a sensitive, simple, portable, and accurate instrument which will detect disease and environment change quickly (Farrell et al. 2013).

Nanotechnology could be used to develop instruments which can diagnose the disease at the molecular level, whether it is at the genomic scale or biochemical level. Traditional instruments are not able to perform this act as per estimation due to their large size and less sensitivity. Nanoparticles having small size interact appropriately with small biomolecules at genetic as well as expression level and enabling nanosensors to diagnose the disease at the earliest. In living beings, biochemical reactions like the folding of proteins, DNA replication, translation, cell movement, and cell proliferation are regulated at a small concentration of molecules which could be easily targeted using nanoscience (Wanekaya et al. 2006). It found great use in agriculture as food demand is increasing and disease incidences also because of climate change (Lakhran et al. 2017; Kumar et al. 2019).

5.5.1.1 Quantum Dots

The quantum dots (QDs) are spherical in shape, small size, fluorescent, and crystalline particles, which release its excitons in the surrounding completely covering the three dimensions (Jaiswal and Simon 2004). So, it is found suitable for its high use in disease detection. Bruchez et al. 2013 and Chan and Nie (1998) initially used QDs for biological detection. Afterwards, its use in labelling of the cell, tracing, and diagnosing become very high. Its photostability and optical sensitivity made it the best material to be used in the biomedical industry. The QDs are arranged in various shapes and forms using nanotechnology for bioconjugation. Therefore, the development of QDs and its use in early and accurate disease detection proved a boon in the agriculture sector.

5.5.1.2 Biosensors

The biosensor is another instrument used to detect disease effectively. Biosensor integrates an electronic component with a biological component which results in a measurable signal component. Here transducer recognizes the biological component and electronic component perform signal processing. Higher specificity and sensitivity of biosensors in comparison to traditional sensors is due to bioreceptor, which is further combined with transducer and this resultant biosensor will produce a specific signal. Use of nanoscale material for the detection of the biological signal will provide us with NBS.

Nano-biosensor has the advantage of being a smaller size, reliable, accurate, portable, fast, reproducible, precise, stable, quantitative and robust compared to conventional ones (Farrell et al. 2013). In agriculture, we apply various fertilizers and pesticides when symptoms of their deficiency and infection are visible in crops which are very late and cause much loss of crops. Therefore, these applications are used mainly as preventive treatment not as a curative method. Nanosensors being specific and ultra-sensitive can detect the infections and nutrients deficiency at the initial stage and kill the pathogens, also cure the disease, so acting as a curative agent. Nanoparticles release the active agents of pesticides, fungicides, and bactericides at controlled rates. They help in precision farming by detecting diseases at the initial level and targeting the biomolecules. These sensors are already in use in many developed countries. To sense, the low amount of DNA concentration in a hybridization reaction is detected using Au NPs-based micro cantilever-based DNA nano-biosensor (Brolo 2012).

The NBS comprises of three components (Espinosa et al. 2015 Habibi and Vignon 2008):

1. Biological sensitive probe: This instrument component detects the biological activity by sensing the number of biomolecules. Some examples of biomolecules

interaction are (a) nucleic acid interactions, (b) antibody–antigen, (c) cell-to-cell interactions (i.e., microorganisms, proteins), and d) enzymatic interactions.

2. Transducer: It is a physical element and senses the biological response and converts that into digital signals. Nanomaterials properties sense different optical, electrochemical, and mass-sensitive messaging signals.
3. Data taping section: This acted as a signal processor and amplifier and mediated data transferred and stored.

Subsequently, nano- and microscale network devices are employed in a hierarchical arrangement to monitor plant growth at different stages. Furthermore, the control units manage the nanosystems and data flow, which at a later stage is directed to the internet (Dufresne et al. 2000). Use of nanonetworks of signaling and transducing component for regulating plant state will by design tell about the requirement and growth condition of crops and results in better resource use. Thus, the real-time checking of the development in the crop will help in better decision making at the right time, reduced costs by reducing the use of disease controlling chemicals and minimum agriculture wastage, improved quality of yield, and principally sustainable agriculture.

Finally, NBS use for high-resolution crop plants evaluation could prove a functional tool for further research work. Continuous real-time monitoring of phytometabolites and phytohormones using NBS plays more insights into learning of plant biosynthetic cycles and their regulation, which will help in getting desired products by controlling pathways via the use of various chemicals (Accenture Technology Labs 2004).

Carbon Nanomaterials as a Sensor Carbon is used in biosensors for biochemical analysis. Carbon nanosensors which could be carbon nanotubes or dendrimers detect small molecular signals, which initiate a chemical or electrical response. Some sensors operate by stimulating an enzyme-catalyzed reaction. Contaminants and pathogens are detected by minimum use of time with increased sensitivity.

5.5.2 Disease Control

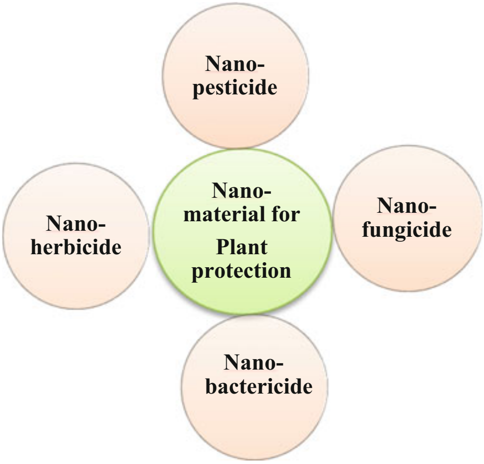
Once the disease is detected, the next step will be controlling the disease using different chemical and biological agents and by the alternation of environmental conditions which support the pest attack. Traditionally, disease control measures include the use of pesticides and herbicides. Nevertheless, these agents show boosted activity at the nanoscale. Use of nanoscience in various crop management techniques is employed to improve resource use. Various diseases like bacterial, fungal, and viral could be detected at an early stage and controlled using NPs. Table 5.4 entails the details of various nanomaterials used as antiviral agents to prevent a specific group of viral infections.

Diverse types of NPs, for example, nanosilver, nano aluminosilicate, TiO_2 NPs, carbon nanomaterials, and magnetic NPs have applications as antimicrobial agents.

Table 5.4 Antiviral activity of NPs

Nanoparticles	Mechanism employed in antiviral activity	Microbes prevented by NPs	Reference
Ag NPs	Stopping binding of the virus to the cell surface	Herpes simplex virus, influenza virus, HIV-1 (human immunodeficiency virus)	Lu et al. (2008) and Lara et al. (2010)
TiO2 NPs		Influenza virus, inactivates bacteriophages, viruses HSV-1	Hajkova et al. (2007), Nakano et al. (2012), and Syngouna and Chrysikopoulos (2017)
Au NPs		Influenza virus and HIV	Lara et al. (2010) and Di Gianvincenzo et al. (2010)
ZnO NPs		Transmissible gastroenteritis virus	Antoine et al. (2012) and Chai et al. (2014)

Fig. 5.2 Various types of nanomaterial for disease control in crops



Among all, silver NPs found extensive use as an antimicrobial substance, and their production became economical with the advancement in technology. Thus, the potential employment of nanocomposites was measured as an effective and better alternative in the prevention of pathogens, and along with these properties, these are economical and environment friendly. Figure 5.2 shows the different nanomaterials used to control biological stresses. Nanocomposites mediated higher penetration in the cuticle layer of leaf and controlled and regulated the release of active component ingredients having disease controlling activity, by targeting the weed site. Thus, the use of these nano biopesticides is preferred as these have improved targeting of weed at low concentration of pesticide use and causing lesser harm to the environment.

Other variants of nano-pesticides are provided with the magnetic NPs with the improved site-targeted release of drugs for a range of diseases treatment in the type of biomedicines (Jurgon et al. 2006). Nonetheless, in plant science, these applications are still in their nascent stage. These magnetic property-based nanomaterials could find application in the site-targeted release of plant defending medicines for the cure of the disease that targets only a particular area of the crop plant.

Nano-pesticides: Insect pests are one of the chief determinants in crop yield, found in the agriculture field as well as in agriculture products. Pesticides are the primary solution used to prevent pest infestation. However, there are concerns regarding the adverse effects of pesticides such as environmental contamination, mammalian toxicity, and bioaccumulation. Nano-pesticides are the new material of nanoscale dimension for efficient delivery of pesticides. “Nano-encapsulation” can be employed to enhance the insect-killing property and to stop environmental contact with the active ingredients of pesticides. Restricted discharge of pesticides is used for further enhancing the efficiency in resource use. Nano-sized active ingredients of pesticides are enclosed in a membrane or sac to employ controlled release.

Sasson et al. (2007) stated the benefits of the use of nano-pesticides, which are as follows:

1. Improved solubility of such active ingredients of pesticides which are sparingly soluble in water.
2. The higher stability of formulations.
3. Removal of toxic organic solvents compared to traditional pesticides.
4. Controlled release of active ingredients of nano-pesticides.
5. Enhanced stability to prevent early degradation.
6. Due to smaller size, higher insecticidal activity, and improved mobility.
7. Enhanced longevity due to the larger surface area.

These all properties result in enhanced RUE with better targeting at a low amount of pesticide. Nanoparticles loaded with insecticides came into the market in 2000 (Feng and Peng 2012). After this, many compounds with active pesticidal effect are loaded with NPs. Silica, chitosan, and lipids are the most used carriers in nanoformulations, and the most targeted pathogens are *Helicoverpa armigera*, *Spodoptera litura,* and *Tetranychus urticae* (Feng and Peng 2012; Lu et al. 2013; Zhang et al. 2013). The recent advancement in the improvement of nano-pesticides is the slow release of active components with improved dissolution, permeability, specificity, and steadiness (Bhattacharyya et al. 2016). These nano-pesticides have found only limited application till now; however, some companies are promoting “microencapsulated pesticides.” Few examples of these nano-pesticides are Syngenta products in Switzerland which includes Subdue Penncap-M, MAXX, Karate ZEON, Ospray’s Chyella and BASF membrane-enclosed pesticides product (Gouin 2004). Syngenta corporation situated in Australia released a few items, for instance, the Banner MAXX, Primo MAXX, Subdue MAXX, etc., which are of nanoemulsion nature (Gouin 2004). These nanoencapsulated pesticides permit less release of pesticides into the environment and so less exposure of humans to these toxic pesticides. Organic capsulation could be developed to make this more useful (Gouin 2004). Sparingly soluble pesticides have been loaded with chitosan (Campos et al. 2018), and silica showed better solubility and interaction with pest (Wang et al. 2014). Stopping of cell multiplication in *S. litura* cells of the ovary and nonstop and controlled discharge of drugs component on the application of chitosan NPs loaded with insecticide azadirachtin have been observed (Lu et al. 2013). Similarly, application of dendrimers loaded with hydrophobic thiamethoxam showed a boost in absorption and death of *H. armigera* larval cell at large scale which otherwise under reasonable condition is not susceptible to thiamethoxam (Liu et al. 2015). Interestingly, dendrimer NPs loaded with the drug showed higher toxicity against *H. armigera*. A rise in death rate was also observed after anacardic acid (liquid extract from cashew nutshell) was complexed with layered double hydroxide (LDH) nano-formulations (Nguyen et al. 2015). In this study, LDH formulation showed a higher death rate of *S. litura* as compared to anacardic acid alone when these formulations are sprayed directly over the skin of pest. Thus, it showed improved activity by the use of nanoformulations, which showed improved results because of enhanced solubility of active ingredients of drugs. These formulations also reduce the loss of active compounds by volatilization or evaporation as these are encapsulated in case of nanoformulations.

Other examples include the use of active ingredient coated aluminosilicate nanotubes. These pesticides in the form of nanotubes are easily picked by insects through the insect hairs from the plants and consumed by the insect and thus better target the insect pest (Torney 2009; Patil 2009). The benefit of the use of this nanostructure is environmentally friendly and higher bioactivity against pests. Better DNA and chemical delivery are elucidated by the silica NPs having mesoporous silica NPs; thus, it can be engaged in better-specified release of active components of drugs and nucleic acid. Essential oil, which is known for its insecticidal properties, is limiting at their high evaporation rate. Essential oils quickly evaporate facilitated by higher chemical volatility on exposure to air, high heats, light, and humidity (Lai et al. 2006). Yang et al. (2009) stated 80% mortality of red flour beetles (*Tribolium castaneum*) in case of treatment with polyethene glycol covered garlic (*Allium sativum*) oil and fats in harvested rice as compared to essential oil alone treatment which showed 11% mortality.

An added motive to build up insecticides of nano dimensions is to extend the shelf life of the biologically active compounds and supply constant unleashes, which may leave a reduction in insect powder employment and better protection. In the agriculture field, Kumar et al. (2014) observed in okra crop (*Abelmoschus esculentus*) inoculated with sodium alginate capsulated nano insecticide incorporated with imidacloprid has shown similar effectivity like imidacloprid on its own. Song et al. (2012) observed improved resistance in Chinese *Brassica* treated with silica-encapsulated chlorfenapyr against the diamondback rattlesnake lepidopteron (*Plutella xylostella*) in three-day treatment. An additional work showed that treating termites by fipronil, laden into nanoformulations having a silicon oxide

(SiO_2) shell prevented the preliminary burst of termites (Wibowo et al. 2014). Silica-laden fipronil increased the cent per cent morbidity window next to 3 days, allowing higher removal of the insect colony compared to the business insect powder. In another case, Jenne et al. (2018) laded organic compound on top of chitosan nanoparticles and checked the impactivity over one hundred eighty days in groundnut bruchid preserving circumstances. Extract of seed's kernel, loaded onto oxide nanoformulations, has groundnut bruchid with 54. The 61% weight is lost compared to the opposite composition tested. Controlled unleash of active ingredients might additionally doubtless reduced the negative results of the pesticides. Up to now, four experiments elucidated, if continued unleash of pesticides from nanocomposites might cause reduced toxicity. As an example, once checking of toxicity of imidacloprid laden over sodium alginate nanocomposites, Kumar et al. (2014) observed reduced harmful effect in case of nanoformulations of pesticides used than the real pesticides.

5.5.2.1 Nano-fungicides

Fungicides are chemical compounds which kill the fungus and prevent a fungal infestation in crops. Development of nano-fungicides starts with the incorporation of fungicides into the robust wood way back in 1997 (Liu et al. 2001). Since then, many nano-fungicides were synthesized using different fungicides and NPs as mentioned in Table 5.5. Like pesticides here also target properties are solubility, stability, and volatility. Silica and chitosan are the most commonly used NPs carriers for the fungicide transfer to plants. Antifungal effectiveness of nanosilver mixture (diameter 1.5 nm) solution, in opposition to rose powdery mildew, attributed to the infestation of *Sphaerotheca pannosa* (Kim et al. 2008a, b). This infestation is the highly prevalent and universal malady of both greenhouse and outside planted roses. Its

Table 5.5 Antifungal activity of NPs

Nanoparticles	Mechanism employed in antifungal activity	Microbes prevented by NPs	Reference
Ag NPs	Damaging of the plant cell membrane	*Trichophyton mentagrophytes, Candida.* Spp.	Kim et al. (2008a, b)
ZnO NPs		*Penicillium expansum, Botrytis cinerea*	He et al. (2011) and Yehia and Ahmed (2013)
TiO_2 NPs		*Candida* spp., *P. expansum*	Rajakumar et al. (2012) and Gomez-Ortiz et al. (2013)
Magnesium oxide (MgO) NPs		*Saccharomyces cerevisiae, Candida albicans*	Sawai and Yoshikawa (2004)
Au NPs		*Aspergillus flavus, Puccinia graminis tritici*	Jayaseelan et al. (2013)
SiO_2 NPs		*Campylobacter* spp.	Zamani et al. (2014)

symptoms include foliar deformation, leaf turning, premature shedding of leaves, and lesser flowering. Binary capsulated nanosilver has been synthesized with the help of physical methods, use of reducing chemicals, and sequestrants via chemical catalysis of nanosilver. It is applied on plants in the form of foliar mist in preventing rot, molds, fungus, and many additional crop plant maladies. Furthermore, nanosilver boosts up plant development.

Nano-fungicides exhibit controlled discharge of active elements to stop the fungal infestation. This slow release of fungicide has been evident from the application of validamycin and calcium carbonated encapsulated validamycin simultaneously against *Rhizoctonia solani*, in the first-week nanoformulations efficiency was lesser compared to validamycin alone, but after 2 weeks, nano-capsulated validamycin showed higher efficiency which shows that fungicide release slow and for more extended time periods (Qian et al. 2011). In the same way, carbendazim-laden polymeric NPs applied in opposition to *Aspergillus parasiticus* and *Fusarium oxysporum* showed the enhanced fungal inhibition rate, and it also showed higher sowing and root expansion of *Lycopersicum esculentum, Zea mays,* and *Cucumis sativa* seeds (Kumar et al. 2017a, b, c).

5.5.2.2 Nano-bactericides

Bactericides are widely used to stop bacterial diseases by killing bacteria. Nano-bactericides are NPs whose size falls in nanometer scale, that is, 1–100 nm (Edmundson et al. 2013). Nanomaterials exhibit a vast range of bactericidal activity in opposition to bacteria. Different types of nanoformulation show different activity based on the uniqueness of NPs and means of action it adopts against bacteria. Nanoparticle physical structure itself is the inherent feature to act against bacteria by a damaging membrane as observed with the graphene oxide NPs (Akhavan and Ghaderi 2010). Another mechanism is the higher discharge of antibacterial charged metal ions from the face of nanomaterial. An additional feature which contributes towards high activity is the small surface to volume ratio through better interaction with the bacterial surface. Most relevant variables which determine antibacterial activity are particle shape, particle size, biochemistry, and zeta potential. The NPs have path breaking as a novel material to triumph over microbial multidrug resistance faced globally due to overuse of antibiotics because NPs act on the membrane in contrast to antibiotics, which get into the cell and cause antimicrobial resistance (Wang et al. 2017). The Ag nanoparticle is the majorly premeditated and applied particle of the biological system. Silver NPs have been considered to have a great prohibitory and bactericidal property in addition to a wide range of antimicrobial behavior (Sondi and Salopek-Sondi 2004). These NPs garner a larger surface area and elevated portion of surface atoms, with a better antimicrobial response in opposition to the Ag alone. Titanium dioxide photo-catalyst method has good potential in plentiful agricultural application, such as plant defense as it did not form harmful and hazardous compounds and have immense pathogen and pest disinfection potential (Yao et al. 2009). Researchers are attempting to enhance the plant's pathogenic medical care potency of TiO_2 nanoformulations by stain addition doping and different appropriate ways (Yao et al. 2009).

Table 5.6 Antibacterial activity of nanoparticles

Nanoparticles	Mechanism employed in antibacterial activity	Microbes prevented by nano-bactericide	Reference
Ag NPs	Inhibits the bacterial activity by damaging the membrane, DNA, and membrane lipids via generation of ROS which inhibits the enzyme activity	*Escherichia coli, Bacillus subtilis, Staphylococcus aureus*	Feng et al. (2000), Smetana et al. (2008), and Jung et al. (2008)
Au NPs		*Vancomycin-resistant Enterococcus faecium, Methicillin-tolerant S. aureus*	Gil-Tomas et al. (2007) and Perni et al. (2009)
TiO_2 NPs		*S. aureus, E. coli*	Matsunaga et al. (1988) and Kim et al. (2003)
ZnO NPs		*E. coli 0157:H7*	(Jiang et al. 2009)
Copper oxide NPs		*Listeria monocytogenes, B. subtilis*	Cioffi et al. (2005) and Ren et al. (2009)
MgO NPs		*E coli,*	Koper et al. (2002)
CaO NPs		*S. aureus, Staphylococcus epidermidis*	Sawai (2003) and Roy et al. (2013)
Al_2O_3 NPs		*E. coli, Pseudomonas aeruginosa*	Li and Logan (2004) and Prashanth et al. (2015)
SiO_2 NPs		*S. mutans*	Silvestry-Rodriguez et al. (2007)
Clay NPs		*P. aeruginosa, E. coli, Enterococcus faecalis*	Haydel et al. (2007) and Bagchi et al. (2013)

The calcium oxide (CaO) and MgO NPs show microbicidal activity by the synthesizing superoxide over the face and by an increase of pH because of water treatment with CaO and MgO water. The aluminum oxide (Al_2O_3) NPs bind with membrane and increase permeability by the destruction of the membrane (Beyth et al. 2015). The ZnO NPs inside the cell discharge metal ions whose band edge structure cause the production of three types of ROS which damage the cell membrane and cell wall of bacteria (Sirelkhatim et al. 2015). Table 5.6 highlights the different NPs possessing bacterial activity against a specific group of bacteria. Silicon NPs have excellent biocompatibility and considered as nontoxic. Silica nanowires exhibit biocidal activity by interfering cell functions, for instance, cell adhesion, differentiation of cells, and dispersal of bacteria (Shevchenko et al. 2017). Thus, NPs exhibit antimicrobial action using numerous mechanisms that possibly will differ in individual characteristics, for example, electrical charge, outer appearance, size, surface membranes, etc. facilitating researchers to design new complex antimicrobial compounds for different applications in agriculture.

5.5.2.3 Nano-weedicides/Nano-herbicide

Weeds are abundant in agricultural production systems. Belowground plant parts like rhizome and tubers are not targeted by the herbicide available in the market, which is designed to control weeds. Use of nanoscience can improve the efficacy of herbicides, resulting in higher production of crops. Nano-herbicides help in removing the weeds in an eco-friendly manner and leave no harmful residues in the environment and soil and thus save the environment (Pérez-de-Luque and Rubiales 2009). Herbicides encapsulation in polymeric NPs results in controlled release and better efficacy and no harm to the environment. Various nano-pesticides along with their method of preparation and mechanism of action are put in Table 5.7. The nano-herbicides development focus is on reducing non-target toxicity. Various carriers are used to carry herbicides like montmorillonite earth layer covered by a pH reliant polymer (Han et al. 2010). Other example is amino resultant iron (Fe II, III) oxide nano-sized magnetic particles (Viirlaid et al. 2009), amino-derived Fe (II, III).

The NPs synthesized by using chitosan like the carrier are used for reducing the toxicity of herbicides imazapyr and imazapic (Maruyama et al. 2016). Comparable efficiency was observed for the action of nanoparticle laden and herbicides alone in opposition to the objected weed *Bidens pilosa*. Maruyama et al. (2016) experiment on rhizobacteria showed that both nanoparticle membranes enclosed and herbicides alone did not have an effect on the number of bacteria in the loam. Nevertheless, the researchers noted the biasedness in number of rhizobacteria involved in the N_2 fixing cycle using the NPs-laden herbicide faction with the slightest effect. Similarly, solid lipid NPs particles carrying atrazine and simazine herbicides were reported to be highly effective in damaging their objected *Raphanus raphanistrum* while applied ahead of emergence and as active as herbicides when used after emergence (De Oliveira et al. 2015). Chidambaram (2016) transformed rice residues to the useful NPs and laden these particles by 2,4-D (2,4-dichlorophenoxyacetic acid). They observed to facilitate NPs-laden with 2,4-D has improved herbicides killing action compared to 2,4-D alone in opposition to the crop plants (*Brassica* sp.). Leaching effect in soil was also reduced in the case of nano-size rice husk bound with herbicides. Dos Santos Silva et al. (2011) employed chitosan with paraquat and alginate for exhibiting lesser herbicide leakage inside the soil absorption experiments, against paraquat alone. This study also reported a controlled discharge rate of herbicide which was 2 h more compared to herbicide alone.

Nanoparticles combined with ametryn, atrazine, or herbicides subjected to genotoxicity testing on human white corpuscle and alliaceous plant cell cultures. (Grillo et al. 2012) showed reduced toxicity compared to weedicide alone. Furthermore, treatment of those nano-pesticides with organic and inorganic binding material improved their adhesive properties. Grillo et al. (2014a, b) applied chitosan coating at completely different concentration of compound NPs to enhance adhesion to focus on plants. Grillo et al. (2015) conjointly examined the impact of watery soil materials, a fancy of innate macromolecules within the setting, over chitosan-

Table 5.7 Various nano-pesticides or nano-herbicides and their applications

Carrier system	Agent	Function	Method	Reference
Chitosan or alginate	Paraquat	Minimum environmental loss and better targeting of pests	Pre-gelation of alginate Followed by alginate and chitosan intermixing	Silva Mdos et al. (2011)
Oil or surfactants or water	Glyphosate	Higher efficiency and reduced environmental hazard	Emulsion	Jiang et al. (2012)
Alginate	Azadirachtin	Controlled release	Encapsulation	Jerobin et al. (2012)
Wheat gluten	Ethofumesate	Regulated liberation	Entrapment/ extrusion	Chevillard et al. 2012
Poloxamer or xyloglucan	Tropicamide	High efficiency and reduced toxicity	Encapsulation	Dilbaghi et al. (2013)
Chitosan-saponin, Chitosan/ tripolyphosphate, and cu-chitosan	Chitosan, copper sulfate, saponin	Fungicidal action	Inter-linking	Saharan et al. (2013)
Tripolyphosphate or chitosan	Paraquat	Reduced geno- and cytotoxicity	Encapsulation	Grillo et al. (2014a, b)
Carboxymethyl Chitosan	Methomyl	Regulated liberation	Encapsulation	Sun et al. (2014)
Polyacetic acid-polyethylene Glycol	Imidacloprid	Reduce the toxicity amount	Encapsulation	Memarizadeh et al. (2014)
Calcium or sodium alginate	Imidacloprid	Cell mortality	Emulsion	Kumar et al. (2014)
Si NPs	Pyridoxine, piracetam and pentoxifylline	Perfused brain cells	Suspension	Jampilek et al. (2015)
Chitosan	Imazapyr and imazapic	In testing cell toxicity	Encapsulation	Maruyama et al. (2016)

paraquat nano-herbicide. Alliaceous plant genotoxicity experiments and ecotoxicity assays studies on the algae *Pseudokirchneriella subcapitata* exhibited that chitosan-paraquat nanoformulations, within the irrigated soil presence, minimized the lethality, lightness the necessity of many field experiments in pesticide incorporated nanoparticle study.

5.6 Nanotechnology in Post-Harvest Technology

Post-harvest technology includes packaging, storing, and transporting. Packaging of food is essential to achieve food security, warehousing facilities and optimum condition of storage are lacking in developing countries like India, which cause large-scale food spoilage. This spoilage of food further causes health problems in individuals who consume this food. Packaging should have strength, barrier properties, stability to cold and heat. Use of nanotechnology in food packaging with antimicrobial properties has been achieved. To stop the deterioration in smart packaging, which supplies essential information, is still a big problem to producers and experimentalist. Some food has been facilitated along "nanosensors" for checking the oxidative pathway of edible materials, which response to the food quality change by changing the color of packaged material. Nanoparticles act as an excellent barrier to gases, for example, CO_2 and oxygen, therefore, could be used for effective wrapping of food material. Nanoparticles also slow down oxidation and degradation of food and in turn increase the shelf life of food. Some foods that need to maintain a particular amount of CO_2 in their packaging could be packaged in the nanomaterial substance, which increases packaging efficiency by decreasing the CO_2 loss. Plastic material most commonly used could be coated with nanomaterial to improve the packaging quality in the food industry (Berekaa 2015). Nanoparticles coated material also acts as an antimicrobial agent and thus useful for agriculture biosafety, one such example is the silver NPs used in coating act as an antibacterial agent (Bumbudsanpharoke and Ko 2015).

Nanoparticles having bioactive compounds, which have antibacterial properties from oregano oil, cinnamon oil, Ag, chloride, and Zn, have been used in packaging of food (Liakos et al. 2015; Liakos et al. 2017). Organic corn or lobster shells, which have mutually antibacterial and recyclable characteristics, are used for making nanofibers, which promote green packaging of food material. One such product "Durethan" has been composed by Bayer Polymers Company using nanoformulations of silicates NPs, these prevent the oxygen concentration and maintain mandatory moisture, aiding in maintaining health food (http://www.plastemart.com). Other NPs used in packaging are Ag, magnesium, and ZnO particles (Lizundia et al. 2018). Use of radiofrequency technology in labelling of food items will enhance the detection in less time in comparison to bar code reading. These packaging methods could also use sensors to check chemicals, pathogens, and hazardous chemicals in packaged food material. Various forms of NPs like nanofibers, nano wheels, and nanotubes are checked to get better food qualities.

Nanosensors found useful in food labelling and help in quick identification of the useful food product. Additionally, NPs with their high absorption capability are used in getting knowledge of the soil chemistry and can imbibe more nutrients and contaminants which further could be used in support of metal and negatively charged pollutant absorption (Li et al. 2016). So, surface biochemistry can aid in pollutant sequestration. A process with significant results of pollutant remediation or dispersion process could take place. Furthermore, metallic type such as Ni be able to be fused with MWCNTs and could be linked with short-ordered TiO_2 particle surfaces, aluminosilicates particle, humic component, and chemical aromatic compounds; moreover, these combinations could act as potent bio-remediator in the nano agriculture organization (Hajirostamlo et al. 2015). These could act as transferring systems for specific food and feeds, and these systems will be environmentally friendly. Nanosystems could also find great places in the pharmaceutical sector for drugs delivery. Intelligent food packaging with the help of biosensors helps to reveal the exact state of food, so this is an excellent tool in post-harvest management of food.

5.7 Nanotechnology for Agriculture Wastes Recycling

As per estimation, estimated one-third of food produced for individual use globally is dumped every year. An estimated 1.6 gigatons (Gt) "primary product equivalents" and 1.3 Gt of eatable part of foodstuff are being wasted worldwide every year. This quantum is approximated against total agriculture yield produce which is 6 Gt (FAO 2013). Thus, the primary purpose should be to make people informed about the tremendous amount of agriculture/food waste. It should be reused and recycled in a better way using the right methods with best technology employment. Nanotechnology could play a decisive role in the recycling of agriculture wastes.

Fertilizers and pesticides used are increasing with increasing food demands with the rise in population. Annual consumption of pesticides is 2.5 million tons in agriculture (Alvarado et al. 2017). This increased use has an adverse impact on the environment, public health, food quality, and generating resistance in pests. During the application of pesticides, estimated 90% of pesticides are lost in the atmosphere, so a better system of application is needed. Here we found a great use of nanotechnology in the safe use of chemicals in agriculture, by delivery of critical nutrients to the plants and in sensing nutrient deficiency via electronic tools or NBS (De Oliveira et al. 2014). Nanotechnology helps in transferring and reuse of fertilizers and pesticides residues; otherwise, these residues cause pollution for their high use in agriculture. Bioaccumulation of these agriculture residues has been found in marine and land species of animals, even after many years (Baruah and Dutta 2009). Consequently, the efficient use of agricultural inputs is focused on agriculture to avoid waste generation. Nanoparticles are used for fertilizers, pesticides, and growth stimulant production. These particles are also used in remediating soil polluted with agrochemicals using a mechanism such as controlled discharge of phosphorus from fertilizers which are attainable barely under particular environment, for instance, just nearby surface of the roots of the crop to thwart the little accessibility of phosphorus minerals in crop using severe acidic and basic reaction (Alvarado et al. 2017). Methods are causing accumulation of the ammonium NPs, so that it could be used in recycling for the generation of ammonia. Nanotechnology is also used to check soil conditions on a real-time basis using NBS. Therefore, nanotechnology is used to increase the efficient use of agricultural resources so that a minimum amount of waste is generated.

Fortunately, different types of methods are there for reuse and recycle of farm-produced waste rather than remaining in the surrounding environment. Agricultural remains are produced by production, handing out and harvest of different cereal items, fruits, vegetables, and trees, as well as via stock farming. These farm wastes are produced in huge amount globally and could be used as animal feed or put on fire in the field (Tepe and Dursun 2014). Because of their lignocellulosic character (Chandra et al. 2012), these agriculture residues are employed in manufacturing of goods such as organic acids, different types of biofuels, fodder of high peptide content, aromatic complex molecules, secondary metabolites with biological activity, various microbial pigments, and biocatalyst the identical to reactants molecules (Singh Nee Nigam and Pandey 2009).

Nanotechnology causes the changes at the molecular and atomic level and changes the properties of molecules so that specific contaminant to be detected. Nanosensors are developed to detect the contaminant at the early stage and in small quantity precisely and efficiently. According to Ruud J.B. Peters et al. (2016), nanoencapsulated pesticides used in agriculture account for approximately 26%. Inorganic nanomaterials are used in the percentage of 6% clay, 6% of organic materials, 26% metal oxide in addition to 29% metal. Chitosan is used as a biocide and also as food-binding substance (Peters et al. 2016).

5.7.1 Nanomaterials for Remediation

Remediation is the use of chemical/biological agents to abate pollutants. Nanotechnology found their use in pollution abatement. Carbon nanotubes are employed as a sensor to sense hydrogen sulfide, sulfur dioxide, in the absorption of zinc fluoride and water dichlorobenzene and in the absorption of lead, Cu, and cobalt ion (Das et al. 2015). Carbon nanotubes are substitute's activated carbon which has interacting sites for large molecules. Carbon nanotubes are used to eliminate antibiotics and polar aromatics which are not quickly abated by use of other technology. It acts as both electron donor and acceptor and easily remediates wastes. Because of its fibrous composition, better conductivity, and bactericidal nature, it acts as antimicrobial filters (Qu et al. 2012). Iron is used in arsenic removal and barium ions and nitrate removal from water. Titanium dioxide found application in photovoltaic cells, phenol decomposition using light and in removing benzene and toluene compounds (Das et al. 2015). Nano silica particles are better performing antibacterial agent, which performs constriction of *Tribolium castaneum*, *Sitophilus oryzae*, *Lipaphis pseudobrassicae* pests, and thus applied as a pesticide. Nano silica possibly will also study nano ZnO as an antifungal oxide against pathogenic microbes *Fusarium oxysporum* (Qu et al. 2012).

If we consider wastes from agriculture, the majorly produced component as waste is cellulose fibers; it is present in large quantity in the environment and could be extracted from nearly any type of plantation and crop (Carchi 2014). Plants part such as pseudo stem possesses 37.85% cellulose content, whereas flower twig possesses 26.86% cellulose content (Carchi 2014). The significance of getting it contained in the chance of substituting definite synthetic fibers which might be contaminating the surrounding environment and get the advantage of different types of features and characteristics by using nanoscale compounds, delivered by cellulose along with other parts of the plant source, for example, hemicelluloses and lignin component, in the production of few goods of the industrial source (Carchi 2014).

The nano cellulose possesses excellent properties, for example, the low density of nano cellulose particles and a large reactive surface area, having hydroxyl groups which support biding of a definite number of chemicals so that these possibly attain novel surface characteristics. This substituting potential enables the self-congregation ability and management of particle–particle contact, in addition to the particle to matrix interaction. In addition to this, these possibly will be transparent and have improved tensile strength with reduced thermal coefficient extension. In terms of their application, these possibly are reported as reuse for polymers synthesis, biomedical compounds, pharmaceuticals compounds production, synthetic fibers and textiles items, antimicrobial membranes, high-efficiency supercapacitors, among others (Moon et al. 2011). Also, other research has proved that the manufacturing of bioplastics materials prepared using nano cellulosic materials. They used the biomass of banana waste to synthesize nano cellulose which showed useful properties such as reduced water assimilation, a particle dimension of 20 nm, and improved stress along with other properties (Sharif Hossain et al. 2016).

The green nanotechnology concept is in high use in nanoscience. It combines the principle of green chemistry and natural engineering for generating environment-friendly, safe NPs which are not using hazardous chemicals in their making process (Castro et al. 2011). Thus, the making of nanocomposites of metals using Au is of immense use. Nevertheless, the current method of AuNPs formation involves the harmful substances such as dimethylformamide, hydrazine and sodium borohydride chemical compound and chemical agents as reducing substance and possibly demands the use of costly equipment (Krishnaswamy et al. 2014). Here the use of organic components should be promoted instead of harmful chemicals in NPs formation. For making further use of grape waste: a new production of AuNPs using residual farm substances like skin, seed, and stalk of grape is carried out to investigate the generation of nano Au particles. Previously, AuNPs were produced by using grape pomace and grape wine in minimizing nano Au particles using fifty watts of microwave potential (Baruwati and Varma 2009).

5.7.2 Crops Residues for Nanoparticle Synthesis

1. *Rice waste residues*—Rice waste is the most obtained rice residues containing cellulose in the concentration ranging from 28.7 to 35.6%, hemicellulose ranging from 12.0 to 29.3%, and lignin ranging from 15.4 to 20.0% (Isikgor and Becer 2015). It also contains elevated silica amount ranging from 8.7 to 12.1% in amorphous hydrated SiO_2 (Ding et al. 2005). Many researchers have mentioned the formation of husks-derived SiO_2 NPs by using separate methods. The SiO_2

NPs were synthesized from rice husk using the acid-washed technique (Le et al. 2013). The calcium treatment of rice husk waste at temperature 700 °C for 2 hr leads to the synthesize SiO_2 NPs sizing 70 nm, having surface area 241.1 $m^2\ g^{-1}$ (meter square per gram) (Chen et al. 2013).

2. *Sugarcane leaves and bagasse*—Bagasse is the primary sugarcane agricultural residue from ethanol and sugarcane commercial entities. Pereira et al. (2015) stated that changing the surface characteristics and constancy of middle-sized pores passing gamma-alumina by employing bayerite at the same time as aluminum origin and sugarcane bagasse as a sacrificial model (Cardoso et al. 2015). Use of biomass as a variant of bayerite enhanced surface area as well as the volume of the pore to the extant 209 $m^2\ g^{-1}$ and 0.44 $cm^3\ g^{-1}$, respectively. The average pore diameter was also maintained from 5.2 to 7.9 nm range by modifying the template to bayerite proportion. The quantity of biomass template has a significant function in deciding the size of TiO_2NPs (Xue et al. 2018).
3. *Bamboo leaf*—Bamboo has been used in the food and building material. Bamboo residues are rich in silica content so used to prepare silica NPs. Rangaraj and Venkatachalam (2017) synthesized 13.8 nm-sized SiO_2 NPs from the ash of bamboo leaf by using the acid-washed technique. Ng et al. (2017) synthesized aluminosilicate zeolite A from bamboo foliage.

5.8 Potential Risk of Nanotechnology

A nanoscience is a useful tool for improving input use effectiveness, water shortage, poor hygienic circumstances, and other analogous problems. Besides agriculture productivity improvement, it found use in the agri-food industry, the advancement of functional foodstuffs which propose health claims, efficient food production methods, augmented shelf life of food items, enhanced traceability plus the safety of food items, and more hygienic food processing. Despite these benefits, it has some detrimental effects also. Less regulation is there for nanotechnology use. Nanoparticles get accumulated in the environment, and there is a risk of transfer from crops to food chain which could have an unfavorable impact on the atmosphere and human well-being (Priester et al. 2012). Inherent NPs, for example, proteins present in milk, large globular structures, DNA, and sugar biomolecules are not risky to the environment, but engineered nanomaterials have potential risk (Gruère et al. 2011). Plants have a crucial function in the transport and accretion of NPS, but biomagnification, bioaccumulation, and biological conversion of artificially prepared NPs are not correctly understood in food crops. Engineered NPs adherence to the roots may cause physical or chemical toxicity in plants. In case of human beings, NPs negative effect on human health have been reported such as inflammation, carcinogenesis and fibrotic lung diseases. The extreme use of fibrous and tubular nanostructure have negative impacts on human health (Oberdorster et al. 2005). The SWCNTs inhibit the cell multiplication inside the kidney by decreasing the cellular adhesive ability and inducing cell apoptosis. They also cause inflammation in the lungs (Oberdorster et al. 2005).

Similarly, MWCNT's persistence inside the lungs causes both inflammation and fibrotic reactions. The presence of integration in the blood–brain barrier is affected by using ion distribution characteristics, and the capability of carbon nanotubes in the brain has been reported (Oberdorster et al. 2005). Oxidative damage and extreme lipid peroxidation have been reported in the brain of fish cells by use of fullerenes. Thus, NPs use has a negative impact on humans as well as an aquatic ecosystem (Lin and Xing 2007).

These nanostructures harm the surroundings and biological system like a high concentration of nano silver treatment acts as chemical hazards on edible plants. Nanoparticles lead to the generation of free charged entities in living cells, amount to DNA breakage, so the use of nanomaterials should be regulated (Dekkers et al. 2016). At present, there are no factual, informative studies regarding the accumulation of nanomaterials in the atmosphere, their distribution, and physicochemical properties although now different models are employed to guess possible discharge and amount accumulation in the environment. As per Klaine et al. (1851), technology development for detection of nanomaterial in the surrounding the atmospheric, aquatic, and terrestrial environment for risk assessment should be at the priority.

5.9 Conclusions

For the advancement of the agricultural division, nanotechnology played an essential role as it can be widely utilized in agricultural items which monitor plant growth, defend plants, and sense diseases. The promising outcome is achieved in the field of nano-nutrients, in defense of crop plants using nano-herbicides or nano-pesticides, improvement of crop productivity, in use of NBS and nano-packing. Nanotechnology is helpful in the achievement of sustainable agriculture, increased crop yield and sustaining environment via the use of nanobiotechnology, nano agrochemicals, and organic and inorganic nanoparticles. Nutrient use efficiency could be achieved using nanoscience by using targeted genetic engineering, targeted nutrient supply, biomolecule delivery, nucleic acid delivery, monitoring physiological responses, environmental sensing, balanced nutrient supply, stimulated crop growth, quality improvement, regulation of nutrient migration to the environment, precision farming, adaptation to progressive climate change, and stress gene expression (Kumar et al. 2017a). Nanoscience is generating novel material to increase productivity and nutrient use efficiency via controlled release of input materials from the nano-fertilizers, nano-pesticides, and nano-herbicides with improved targeting. The scientist could further improve nanoscience tools used in agriculture to batter tackle climate change and food inadequacy. Researchers have been functioning in the direction of finding novel applications of nanotechnology in farming. Therefore, it is required to take the current understanding of nanoscience in the improvement of farming productivity and better nutrient use efficiency. As nanoscience have enormous applications but still consumers and farmers are not adopting these tools and techniques for improving nutrients use efficiency as hazards associated with nanomaterials use are not properly assessed. For best use of this technology, an international collaboration for guidelines formulations, legislation, rules and regulation designing are required with the formation of a comprehensive database for nanomaterial use.

5.10 Future Perspectives

Nanotechnology is a valuable tool to achieve sustainable agriculture. Now it needs to be integrated into various food supply chains to attain the best use of this nanoscale technology. Novel techniques are being adopted with best government policies support to make the most of the production in agriculture. Therefore, the nanotechnology could be seen as an innovative and potential technology that pertains unique and exclusive characteristics in the featured food supply chain. This technology could improve the supply chain from agriculture fields to consumption stage by adopting nanoproducts including nano-herbicides, nano-fertilizers, and nano-pesticides, which would help to achieve the precision farming objectives. It could improve food quality and palatability with better nutrient availability along with better labelling and packaging of food items using nanotechnology at a global scale. Few centered areas might get much attention in close to future advance researches in the field of agricultural technology and non-foods:

- Proper analysis of the properties of nanomaterials in terms of structures, accumulation of NPs, size of particles, surface chemistry, immune reaction, treatment period and retention period, and other outcomes should be assessed cautiously.
- Life-cycle of nano foods or nanomaterials should be assessed.
- The new investigative approach is essential for the development, detection, validation, and assessment of the consequence of every nano-system on the complete environment.
- Development of databank and global cooperation for policy formulation is needed to improve further knowledge in this field.
- In addition to this, clear guidelines should be given by authorized institutions for reducing the negative impact of nanomaterial used in agriculture field.
- This technology in the coming time may give a various pioneering and cost-effective pathway for fulfilling food demands and maintenance of a sustainable environment.

References

Accenture Technology Labs (2004) Remote sensor network: Accenture prototype helps Pickberry vineyard improve crop management. Accenture, New York, p 2004

Afsharinejad A, Davy A, Jennings B, Brennan C (2016) Performance analysis of plant monitoring nanosensor networks at THz frequencies. IEEE Internet Things J 3:59–69

Agrawal S, Rathore P (2014) Nanotechnology pros and cons to agriculture: a review. Int J Curr Microbiol App Sci 3(3):43–55

Ahmad A, Mukherjee P, Senapati S, Mandal D, Khan MI, Kumar R (2003) Extracellular biosynthesis of silver nanoparticles using the fungus *Fusarium oxysporum*. Colloids Surf B Biointerfaces 28:313–318

Akhavan O, Ghaderi E (2010) Toxicity of graphene and graphene oxide nanowalls against bacteria. ACS Nano 4(10):5731–5736

Alvarado MA, Guzmán ON, Solís NM, Vega-Baudrit J (2017) Recycling and elimination of wastes obtained from agriculture by using nanotechnology: nanosensors. Int J Biosen Bioelectron 3 (5):368–375

Anjali CH, Sharma Y, Mukherjee A, Chandrasekaran N (2012) Neem oil (*Azadirachta indica*) nanoemulsion-a potent larvicidal agent against Culex quinquefasciatus. Pest Manag Sci 68:158–163

Antoine TE, Mishra YK, Trigilio J, Tiwari V, Adelung R, Shukla D (2012) Prophylactic, therapeutic and neutralizing effects of zinc oxide tetrapod structures against herpes simplex virus type-2 infection. Antivir Res 96:363–375

AZoNano.com (2003) Nanofibers to be used in drug delivery, gene therapy, crop engineering and environmental monitoring (webpage on the internet). AZoM.com Pty. Ltd, Manchester. (updated June 11, 2013). Available from: http://www.azonano.com/article.aspx?ArticleID=114

Bagchi B, Kar S, Dey SK, Bhandary S, Roy D, Mukhopadhyay TK, Das S, Nandy P (2013) In situ synthesis and antibacterial activity of copper nanoparticle loaded natural montmorillonite clay based on contact inhibition and ion release. Colloids Surfaces B Biointerfaces 108:358–365

Baruah S, Dutta J (2009) Nanotechnology applications in pollution sensing and degradation in agriculture: a review. Environ Chem Lett 7(3):191–204

Baruwati B, Varma RS (2009) High value products from waste: grape pomace extract-a three-in-one package for the synthesis of metal nanoparticles. Chem Sus Chem 2(11):1041–1044

Berekaa MM (2015) Review Article; nanotechnology in food industry; advances in food processing, packaging and food safety. Int J Curr Microbiol App Sci 4(5):345–357

Beyth N, Houri-Haddad Y, Domb A, Khan W, Hazan R (2015) Alternative antimicrobial approach: Nano-antimicrobial materials. Evid-Based complementary Altern Med 2015:246012. https://doi.org/10.1155/2015/246012

Bhattacharyya A, Duraisamy P, Govindarajan M, Buhroo AA, Prasad R (2016) Nano-biofungicides: emerging trend in insect pest control. In: Prasad R (ed) Advances and applications through fungal Nanobiotechnology. Springer International Publishing, Cham, pp 307–319

Brolo AG (2012) Plasmonics for future biosensors. Nat Photonics 6:709–713. https://doi.org/10.1038/nphoton.2012.266

Bruchez M, Moronne M, Gin P, Weiss S, Alivisatos AP (2013) Semiconductor nanocrystals as fluorescent biological labels. Science 281:6

Bumbudsanpharoke N, Ko S (2015) Nano-Food Packaging: An Overview of Market, Migration Research, and Safety Regulations. J Food Sci 80(5):R910–R923

Campos EV, Proença PL, Oliveira JL, Melville CC, Vechia JF, Andrade DJ, Fraceto LF (2018) Chitosan nanoparticles functionalized with-cyclodextrin: a promising carrier for botanical pesticides. Sci Rep 8:2067

Carchi D (2014) Aprovechamiento de los Residuos Agrícolas provenientes del cultivo de Banano para obtener Nanocelulosa. Universidad de Cuenca, Cuenca

Cardoso CS, Licea YE, Huang X, Willinger M, Louis B, Pereira MM (2015) Improving textural properties of γ-alumina by using second generation biomass in conventional hydrothermal method. Micropor Mesopor Mater 207:134–141

Castro L, Blazquez M, Munoz J, González F, García C (2011) Biosynthesis of gold nanowires using sugar beet pulp. Process Biochem 46(5):1076–1082

Chai W, Zakrzewski SS, Günzel D, Pieper R, Wang Z, Twardziok S, Janczyk P, Osterrieder N, Burwinkel M (2014) High dose dietary zinc oxide mitigates infection with transmissible gastroenteritis virus in piglets. BMC Vet Res 10:75

Chan WCW, Nie SM (1998) Quantum dot bioconjugates for ultrasensitive nonisotopic detection. Science 281(5685):2016–2018

Chandra R, Takeuchi H, Hasegawa T (2012) Methane production from lignocellulosic agricultural crop wastes: a review in context to second generation of biofuel production. Renew and Sustain Energy Rev 16(3):1462–1476

Chen H, Wang W, Martin JC, Oliphant AJ, Doerr PA, Xu JF, DeBorn KM, Chen C, Sun L (2013) Extraction of lignocellulose and synthesis of porous silica nanoparticles from rice husks: a comprehensive utilization of rice husk biomass. Sustainable Chem Eng 1:254–259

Cheng HN, Klasson KT, Asakura T, Wu Q (2016) Nanotechnology in agriculture. In: Cheng HN, Doemeny L, Geraci CL, Schmidt DG (eds) Nanotechnology: delivering on the promise, vol 2. ACS, Washington, DC, pp 233–242

Chevillard A, Angellier-Coussy H, Guillard V, Gontard N, Gastaldi E (2012) Controlling pesticide release via structuring agropolymer and nanoclays based materials. J Hazard Mater 20:32–39. https://doi.org/10.1016/j.jhazmat.2011.11.093

Chidambaram R (2016) Application of rice husk nanosorbents containing 2, 4-dichlorophenoxyacetic acid herbicide to control weeds and reduce leaching from soil. J Taiwan Inst Chem Eng 63:318–326

Choy J, Choi S, Oh J et al (2007) Clay minerals and layered double hydroxides for novel biological applications. Appl Clay Sci 36:122

Cioffi N, Torsi L, Ditaranto N, Tantillo G, Ghibelli L, Sabbatini L, Bleve-Zacheo T, D'Alessio M, Zambonin PG, Traversa E et al (2005) Copper nanoparticle/polymer composites with antifungal and bacteriostatic properties. Chem Mater 17:5255–5262

Das S, Sen B, Debnath N (2015) Recent trends in nanomaterials applications in environmental monitoring and remediation. Environ Sci Pollut Res Int 22(23):18333–18344

De Oliveira JL, Campos EV, Bakshi M, Abhilash PC, Fraceto LF (2014) Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture: prospects and promises. Biotechnol Adv 32(8):1550–1561

De Oliveira JL, Campos ENVR, Gonçalves da Silva CM, Pasquoto T, Lima R, Fraceto LF (2015) Solid lipid nanoparticles co-loaded with simazine and atrazine: preparation, characterization, and evaluation of herbicidal activity. J Agric Food Chem 63:422–432

Dekkers S, Oomen AG, Bleeker EAJ, Vandebriel RJ, Micheletti C (2016) Towards a nanospecific approach for risk assessment. Regul Toxicol Pharmacol 80:46–59

Di Gianvincenzo P, Marradi M, Martínez-Ávila OM, Bedoya LM, Alcamí J, Penadés S (2010) Gold nanoparticles capped with sulfate-ended ligands as anti-HIV agents. Bioorg Med Chem Lett 20:2718–2721

Dilbaghi N, Kaur H, Ahuja M, Kumar S (2013) Evaluation of tropicamide loaded tamarind seed xyloglucan nanoaggregates for ophthalmic delivery. Carbohydr Polym 94:286–291. https://doi.org/10.1016/j.carbpol.2013.01.054

Ding TP, Ma GR, Shui MX, Wan DF, Li RH (2005) Silicon isotope study on rice plants from the Zhejiang province. China Chem Geol 218:41–50

Dos Santos Silva M, Cocenza DS, Grillo R, de Melo NFS, Tonello PS, de Oliveira LC, Cassimiro DL, Rosa AH, Fraceto LF (2011) Paraquat-loaded alginate/chitosan nanoparticles: preparation, characterization and soil sorption studies. J Hazard Mater 190:366–374

Dubey A, Mailapalli DR (2016) Nanofertilisers, nanopesticides, nanosensors of pest and nanotoxicity in agriculture. In: Lichtfouse E (ed) Sustainable Agriculture Reviews, vol 19. Springer, Cham, pp 307–330

Dufresne A, Dupeyre D, Vignon MR (2000) Cellulose microfibrils from potato tuber cells: processing and characterization of starch-cellulose microfibril composites. J Appl Polym Sci 76(14):2080–2092. https://doi.org/10.1002/(SICI)1097-4628(20000628)76:143.0.CO;2-U

Edmundson M, Thanh NT, Song B (2013) Nanoparticles based stem cell tracking in regenerative medicine. Theranostics 3(8):573–582

El-Shanshoury AERR, ElSilk SE, Ebeid ME (2011) Extracellular biosynthesis of silver nanoparticles using Escherichia coli ATCC 8739, *Bacillus subtilis* ATCC 6633 and Streptococcus thermophilus ESh1 and their antimicrobial activities. Nanotechnology 10:1–7

Espinosa E, Tarrés Q, Delgado-Aguilar M, González I, Mutjé P, Rodríguez A (2015) Suitability of wheat straw semichemical pulp for the fabrication of lignocellulosic nanofibres and their application to papermaking slurries. Cellulose 23(1):837–852. https://doi.org/10.1007/s10570-015-0807-8

Farrell D, Hoover M, Chen H, Friedersdorf L (2013) Overview of resources and support for nanotechnology for sensors and sensors for nanotechnology: improving and protecting health, safety, and the environment. US National Nanotechnology Initiative, Arlington

Feng BH, Peng LF (2012) Synthesis and characterization of carboxymethyl chitosan carrying ricinoleic functions as an emulsifier for azadirachtin. Carbohydr Polym 88:576–582

Feng QL, Wu J, Chen G, Cui F, Kim T, Kim J (2000) A mechanistic study of the antibacterial effect of silver ions on Escherichia coli and Staphylococcus aureus. J Biomed Mater Res 52:662–668

Food and Agriculture Organization of the United Nations, Europe (2013) Food wastage footprint-impacts on natural resources: Summary report, (available at http://www.fao.org/3/i3347e/i3347e.pdf)

Gao FQ, Liu C, Qu CX, Zheng L, Yang F, Su MG, Hong FH (2008) Was improvement of spinach growth by nano-TiO2 treatment related to the changes of rubisco activase? Biometals 21:211–217. https://doi.org/10.1007/s10534-007-9110-y

Ghormade V, Deshpande MV, Paknikar KM (2011) Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnol Adv 29:792–803

Gil-Tomas J, Tubby S, Parkin IP, Narband N, Dekker L et al (2007) Lethal photosensitisation of Staphylococcus aureus using a toluidine blue O–tiopronin–gold nanoparticle conjugate. J Mater Chem 17:3739–3746

Giraldo JP, Landry MP, Faltermeier SM (2014a) Plant nanobionics approach to augment photosynthesis and biochemical sensing. Nat Mater 13:400–408. https://doi.org/10.1038/nmat3890

Giraldo JP, Landry MP, Faltermeier SM, McNicholas TP, Iverson MN, Boghossian AA, Reuel NF, Hilmer AJ, Sen F, Brew J, Strano MS (2014b) Plant nanobionics approach to augment photosynthesis and biochemical sensing. Nat Mater 13:400

Gomez-Ortiz N, De la Rosa-Garcia S, Gonzalez-Gomez W, Soria-Castro M, Quintana P, Oskam G (2013) Antifungal coatings based on Ca (OH) 2 mixed with ZnO/TiO2 nanomaterials for protection of limestone monuments, ACS Appl. Mater Interfaces 5:1556–1565

Gouin S (2004) Microencapsulation: industrial appraisal of existing technologies and trends. Trends Food Sci Technol 15:330–347

Grillo R, dos Santos NZP, Maruyama CR, Rosa AH, de Lima R, Fraceto LF (2012) Poly (-ε-caprolactone) nanocapsules as carrier systems for herbicides: Physico-chemical characterization and genotoxicity evaluation. J Hazard Mater 231:1–9

Grillo R, Pereira AE, Nishisaka CS, de Lima R, Oehlke K, Greiner R (2014a) Chitosan/tripolyphosphate nanoparticles loaded with paraquat herbicide: an environmentally safer alternative for weed control. J Hazard Mater 27:163–171. https://doi.org/10.1016/j.jhazmat.2014.05.079

Grillo R, Rosa A, Fraceto LF (2014b) Poly (ε-caprolactone) nanocapsules carrying the herbicide atrazine: effect of chitosan-coating agent on physico-chemical stability and herbicide release profile. Int J Environ Sci Technol 11:1691–1700

Grillo R, Clemente Z, de Oliveira JL, Campos EVR, Chalupe VC, Jonsson CM, de Lima R, Sanches G, Nishisaka CS, Rosa AH (2015) Chitosan nanoparticles loaded the herbicide paraquat: the influence of the aquatic humic substances on the colloidal stability and toxicity. J Hazard Mater 286:562–572

Gruère G, Clare N, Linda A (2011) Agricultural, food and water nanotechnologies for the poor opportunities, constraints and role of the consultative group on international agricultural research. J Int Food Policy Res Inst 1:35

Gupta A, Kumar A (2018) Climate resilient agro-technologies for enhanced crop and water productivity under water deficit agro-ecologies. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 339–356

Habibi Y, Vignon MR (2008) Optimization of cellouronic acid synthesis by TEMPO-mediated oxidation of cellulose III from sugar beet pulp. Cellulose 15(1):177–185. https://doi.org/10.1007/s10570-007-9179-z

Hager H (2011) Nanotechnology in agriculture. http://www.topcropmanager.com

Hajirostamlo B, Mirsaeedghazi N, Arefnia M (2015) The role of research and development in agriculture and its dependent concepts in agriculture [short review]. Asian J Appl Sci Eng 4. https://doi.org/10.1016/j.cocis.2008.01.005

Hajkova P, Spatenka P, Horsky J, Horska I, Kolouch A (2007) Photocatalytic effect of TiO2 films on viruses and bacteria. Plasma Process Polym 4:S397–S401

Han YS, Lee SY, Yang JH, Hwang HS, Park I (2010) Paraquat release control using intercalated montmorillonite compounds. J Phys Chem Solids 71:460–463

Haydel SE, Remenih CM, Williams LB (2007) Broad-spectrum in vitro antibacterial activities of clay minerals against antibiotic-susceptible and antibiotic-resistant bacterial pathogens. J Antimicrob Chem 61(2):353–361

He L, Liu Y, Mustapha A (2011) Antifungal activity of zinc oxide nanoparticles against Botrytis cinerea and Penicillium expansum. Microbiol Res 166:207–215

Hochella MF, Jr Spencer MG, Jones KL (2015) Nanotechnology: nature’s gift or scientists’ brainchild? Environ Sci Nano 2:114–119. https://doi.org/10.1039/C4EN00145A

Hong F, Zhou J, Liu C, Yang F, Wu C, Zheng L, Yang P (2005) Effect of nano-TiO2 on photochemical reaction of chloroplasts of spinach. Biol Trace Elem Res 105(1–3):269–279. https://doi.org/10.1385/BTER:105:1-3:269. http://www.geohumus.com/us/products.html. Accessed 20 Oct 2016

Isikgor FH, Becer CR (2015) Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers. Polym Chem 6:4497–4559

Jaiswal JK, Simon SM (2004) Potentials and pitfalls of fluorescent quantum dots for biological imaging. Trends Cell Biol 14:497–504. https://doi.org/10.1016/j.tcb.2004.07.012

Jampilek J, Zaruba K, Oravec M, Kunes M, Babula P, Ulbrich P, Braziniova I, Opatrilova R, Triska J, Suchy P (2015) Preparation of silica nanoparticles loaded with nootropics and their in vivo permeation through blood-brain barrier. Biomed Res Int 2015:812673. https://doi.org/10.1155/2015/812673

Jangir CK, Kumar S, Lakhran H, Meena RS (2017) Towards mitigating malnutrition in pulses through biofortification. Trends in Biosc 10(17):2999–3002

Jayaseelan C, Ramkumar R, Rahuman AA (2013) Green synthesis of gold nanoparticles using seed aqueous extract of *Abelmoschus esculentus* and its antifungal activity. Ind Crop Prod 45:423–429

Jenne M, Kambham M, Tollamadugu NP, Karanam HP, Tirupati MK, Balam RR, Shameer S, Yagireddy M (2018) The use of slow releasing nanoparticle encapsulated Azadirachtin formulations for the management of *Caryedon serratus* O. (groundnut bruchid). IET Nanobiotechnol 12:963–967

Jerobin J, Sureshkumar RS, Anjali CH, Mukherjee A, Chandrasekaran N (2012) Biodegradable polymer-based encapsulation of neem oil nanoemulsion for controlled release of Aza-a. Carbohydr Polym 90:1750–1756. https://doi.org/10.1016/j.carbpol.2012.07.064

Jha AK, Prasad K (2010) Biosynthesis of metal and nanoparticles using lactobacilli from yoghurt and probiotic spore tablets. Biotechnol J 5:285–291

Jia LR, Xia J, Zhou N, Chen WY (2008) Preservation of fruits by hydrolyzed collagen/sodium alginate nanoparticles latex. Food Mach 1:46–50

Jiang W, Mashayekhi H, Xing B (2009) Bacterial toxicity comparison between nano and micro-scaled oxide particles. Environ Pollut 157:1619–1625

Jiang LC, Basri M, Omar D, Rahman MBA, Salleh AB, Zaliha RN (2012) Green nano-emulsion intervention for water-soluble glyphosate isopropylamine (IPA) formulations in controlling

Eleusine indica (*E. indica*). Pest Biochem Physiol 102:19–29. https://doi.org/10.1016/j.pestbp.2011.10.004

Joseph T, Morrison M (2006) Nanotechnology in agriculture and food. Nanoforum Report. Institute of Nanotechnology, Evanston, pp 1–13

Jung WK, Koo HC, Kim KW, Shin S, Kim SH, Park YH (2008) Antibacterial activity and mechanism of action of the silver ion in *Staphylococcus aureus* and *Escherichia coli*. Appl Environ Microbiol 74:2171–2178

Jurgon R, Seliger C, Hilpert A, Trahms L, Odenbach S, Alexiou C (2006) Drug loaded magnetic nanoparticles for cancer therapy. J Phys Condens Matter 18:S2893–S2902

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017a) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in indo-Gangetic Plains of India. J Curr Microb Appl Sci 6(3):152–163

Kakraliya SK, Kumar N, Dahiya S, Kumar S, Yadav DD, Singh M (2017b) Effect of integrated nutrient management on growth dynamics and productivity trend of wheat (*Triticum aestivum* L.) under irrigated cropping system. J Plant Develop Scie 9(1):11–15

Kakraliya SK, Kumar S, Kakraliya SS, Choudhary KK, Singh LK (2018a) Remedial options for the sustainability of rice-wheat cropping system. J Pharma Phytochem 7(2):163–171

Kakraliya SK, Singh U, Bohra A, Choudhary KK, Kumar S, Meena RS, Jat ML (2018b) Nitrogen and legumes: a meta-analysis. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 277–314. https://doi.org/10.1007/978-981-13-0253-4_9

Kandasamy S, Prema RS (2015) Methods of synthesis of nano particles and its applications. J Chem Pharm Res 7:278–285

Kashyap PL, Xiang X, Heiden P (2015) Chitosan nanoparticle based delivery systems for sustainable agriculture. Int J Biol Macromol 77:36

Kim B, Kim D, Cho D, Cho S (2003) Bactericidal effect of TiO_2 photocatalyst on selected food-borne pathogenic bacteria. Chemosphere 52:277–281

Kim HS, Kang HS, Chu GJ, Hong SB (2008a) Antifungal effectiveness of nanosilver colloid against rose powdery mildew in greenhouses. Solid State Phenom 135:15–18

Kim KJ, Sung WS, Moon SK, Choi JS, Kim JG, Lee DG (2008b) Antifungal effect of silver nanoparticles on dermatophytes. J Microbiol Biotechnol 18:1482–1484

Klaine SJ, Alvarez PJ, Batley GE, Fernandes TF, Handy RD, Lyon DY, Mahendra S, Mclaughlin MJ (1851) Lead JR (2008) Nanomaterials in the environment, bahaviour, fate, bioavailability and effects. Environ Toxicol Chem 27:1825

Koper OB, Klabunde JS, Marchin GL, Klabunde KJ, Stoimenov P, Bohra L (2002) Nanoscale powders and formulations with biocidal activity toward spores and vegetative cells of bacillus species, viruses, and toxins. Curr Microbiol 44:49–55

Krishnaswamy K, Vali H, Orsat V (2014) Value-adding to grape waste: green synthesis of gold nanoparticles. J Food Eng 142:210–220

Kumar S, Bhanjana G, Sharma A, Sidhu MC, Dilbaghi N (2014) Synthesis, characterization and on field evaluation of pesticide loaded sodium alginate nanoparticles. Carbohydr Polym 101:1061–1067. https://doi.org/10.1016/j.carbpol.2013.10.025

Kumar S, Chauhan N, Gopal M, Kumar R, Dilbaghi N (2015) Development and evaluation of alginate-chitosan nanocapsules for controlled release of acetamiprid. Int J Biol Macromol 81:631–637

Kumar S, Kumar D, Dilbaghi N (2017a) Preparation, characterization, and bio-efficacy evaluation of controlled release carbendazim-loaded polymeric nanoparticles. Environ Sci Pollut Res 24:926–937

Kumar S, Lakhran H, Meena RS, Jangir CK (2017b) Current need of sustainable food and forage production to eliminate food and forage insecurity under current climatic era. Forage Res 44 (1):165–173

Kumar S, Karaliya SK, Chaudhary S (2017c) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. J of Curr Microb Appl Scie s 6 (3):142–151

Kumar S, Meena RS, Jakhar SR, Jangir CK, Gupta A, Meena BL (2019) Adaptation strategies for enhancing agricultural and environmental sustainability under current climate. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 226–274

Kuzma J (2007) Moving forward responsibly: oversight for the nanotechnology-biology interface. J Nanopart Res 9:165–182

Kwak SY, Giraldo JP, Wong MH, Tisdale WA (2017) A nanobionic light-emitting plant. Nano Lett 17:7951–7961

Lai F, Wissing SA, Müller RH, Fadda AM (2006) Artemisia arborescens L. essential oil-loaded solid lipid nanoparticles for potential agricultural application: preparation and characterization. AAPS Pharm Sci Tech 7:E10

Lakhran H, Kumar S, Bajiya R (2017) Crop diversification: an option for climate change resilience. Trends in Biosci 10(2):516–518

Lara HH, Ayala-Nunez NV, Ixtepan-Turrent L, Rodriguez-Padilla C (2010) Mode of antiviral action of silver nanoparticles against HIV-1. J Nanobiotechnol 8:1

Layek J, Das A, Mitran T, Nath C, Meena RS, Yadav GS, Shivakumar BG, Kumar S, Lal R (2018) Cereal+legume intercropping: an option for improving productivity and sustaining soil health. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 347–386. https://doi.org/10.1007/978-981-13-0253-4_11

Le VH, Thuc CNH, Thuc HH (2013) Synthesis of silica nanoparticles from Vietnamese rice husk by sol–gel method. Nanoscale Res Lett 8:58–67

Lei Z, Mingyu S, Chao L, Liang C, Hao H, Xiao W, Xiaoqing L, Fan Y, Fengqing G, Fashui H (2007) Effects of nanoanatase TiO_2 on photosynthesis of spinach chloroplasts under different light illumination. Biol Trace Elem Res 1191:68–76. https://doi.org/10.1007/s12011-007-0047-3

Lei Z, Mingyu S, Xiao W, Chao L, Chunxiang Q, Liang C, Hao H, Xiaoqing L, Fashui H (2008) Antioxidant stress is promoted by nano-anatase in spinach chloroplasts under UV-B radiation. Biol Trace Elem Res 121:69–79

Li B, Logan BE (2004) Bacterial adhesion to glass and metal-oxide surfaces. Colloids Surfaces B Biointerfaces 36:81–90

Li H, Shan C, Zhang Y, Cai J, Zhang W, Pan B (2016) Arsenate adsorption by hydrous ferric oxide nanoparticles embedded in cross-linked anion exchanger: effect of the host pore structure. ACS Appl Mater Interfaces 8:3012–3020. https://doi.org/10.1021/acsami.5b09832

Liakos I, Rizzello L, Hajiali H, Brunetti V, Carzino R, Pompa PP, Athanassiou A, Mele E (2015) Fibrous wound dressings encapsulating essential oils as natural antimicrobial agents. J Mater Chem B 3:1583–1589

Liakos IL, Holban AM, Carzino R, Lauciello S, Grumezescu AM (2017) Electrospun fiber pads of cellulose acetate and essential oils with antimicrobial activity. Nano 7:84

Lin D, Xing B (2007) Phytotoxicity of nanoparticles: inhibition of seed growth. Environ Pollut 150:243–250

Lin S, Reppert J, Hu Q, Hudson JS, Reid ML, Ratnikova TA, Rao AM, Luo H, Ke PC (2009) Uptake, translocation, and transmission of carbon nanomaterials in rice plants. Small 5 (10):1128–1132

Liu Y, Yan L, Heiden P, Laks P (2001) Use of nanoparticles for controlled release of biocides in solid wood. J Appl Polym Sci 79:458–465

Liu XM, Zhang FD, Feng ZB, Zhang SQ, He XS, Wang RF, Wang YJ (2010) Effects of nano-ferric oxide on the growth and nutrients absorption of peanut. Journal of Plant Nutrition and Fertilizer Sci 11(4):551

Liu X, He B, Xu Z, Yin M, Yang W, Zhang H, Cao J (2015) A functionalized fluorescent dendrimer as a pesticide nanocarrier: application in pest control. Nanoscale 7:445–449

Lizundia E, Goikuria U, Vilas JL, Cristofaro F, Bruni G, Fortunati E, Armentano I, Visai L, Torre L (2018) Metal nanoparticles embedded in cellulose nanocrystal based films: material properties and post-use analysis. Biomacromolecules 19:2618–2628

Lu L, Sun R, Chen R, Hui CK, Ho CM, Luk JM, Lau GK, Che CM (2008) Silver nanoparticles inhibit hepatitis B virus replication. Antivir Ther 13:253

Lu W, Lu ML, Zhang QP, Tian YQ, Zhang ZX, Xu HH (2013) Octahydrogenated retinoic acid-conjugated glycol chitosan nanoparticles as a novel carrier of azadirachtin: synthesis, characterization, and in vitro evaluation. J Polym Sci Part A Polym Chem 51:3932–3940

Lyons K (2010) Nanotechnology: transforming food and the environment. Food First Backgr 16:1–4

Ma L, Liu C, Qu C, Liu J, Gao F, Hong F (2008) Rubisco activase mRNA expression in spinach: modulation by nanoanatase treatment. Biol Trace Elem Res 1222:168–178. https://doi.org/10.1007/s12011-007-8069-4

Malarkodi C, Rajeshkumar S, Vanaja M, Paulkumar K, Gnanajobitha G, Annadurai G (2013) Eco-friendly synthesis and characterization of gold nanoparticles using Klebsiella pneumonia. J Nanostr Chem 3:2013

Maruyama CR, Guilger M, Pascoli M, Bileshy-José N, Abhilash P, Fraceto LF, de Lima R (2016) Nanoparticles based on chitosan as carriers for the combined herbicides imazapic and imazapyr. Sci Rep 6:23854. https://doi.org/10.1038/srep23854

Matsunaga T, Tomoda R, Nakajima T, Nakamura N, Komine T (1988) Continuous sterilization system that uses photo semiconductor powders. Appl Environ Microbiol 54:1330–1333

Maysinger D (2007) Nanoparticles and cells: good companions and doomed partnerships. Org Biomol Chem 5(15):2335–2342

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016aa) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clea Prod 112(1):1258–1260

Meena RS, Gogoi N, Kumar S (2016bb) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359

Meena BL, Fagodiya RK, Parjapat K, Kaledhonkar MJ, Sharma PC, Meena RS, Mitran T, Kumar S (2018) Legume green manuring: an option for soil sustainability. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 387–408. https://doi.org/10.1007/978-981-13-0253-4_12

Meena RS, Kumar V, Yadav GS, Mitran T (2018a) Response and interaction of Bradyrhizobium japonicum and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regula 84:207–223

Meena RS, Kumar S, Bohra JS, Lal R, Yadav GS, Pandey A (2019) Response of alley cropping-grown sesame to lime and Sulphur on yield and available nutrient status in an acidic soil of eastern India. Energ Ecol Environ 4:65–74

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Memarizadeh N, Ghadamyari M, Adeli M, Talebi K (2014) Preparation, characterization and efficiency of nanoencapsulated imidacloprid under laboratory conditions. Ecotoxicol Environ Saf 107:77–83. https://doi.org/10.1016/j.ecoenv.2014.05.009

Moon R, Martini A, Nairn J, Simonsenf J, Youngblood J (2011) Cellulose nanomaterials review: structure, properties and nanocomposites. Chem Soc Rev 40(7):3941–3994

Nair R, Varghese SH, Nair BG, Maekawa T, Yoshida Y, Kumar DS (2010) Nanoparticulate material delivery to plants. Plant Sci 179:154–163

Nakano R, Ishiguro H, Yao Y, Kajioka J, Fujishima A, Sunada K, Minoshimo M, Hashimoto K, Kubota Y (2012) Photocatalytic inactivation of influenza virus by titanium dioxide thin film. Photochem Photobiol Sci 11:1293–1298

Ng EP, Chow JH, Mukti RR, Muraza O, Chuan Ling T, Wong KL (2017) Hydrothermal synthesis of zeolite from bamboo leaf biomass and its catalytic activity in cyanoethylation of methanol under autogenic pressure and air conditions. Mater Chem Phys 201:78–85

Nguyen TNQ, Le VA, Hua QC, Nguyen TT (2015) Enhancing insecticide activity of anacardic acid by intercalating it into mgal layered double hydroxides nanoparticles. Institut für Abfallwirtschaft und Altlasten, Fakultät Umweltwissenschaften, Technische Universität Dresden, Dresden

Oberdorster G, Maynard A, Donaldson K (2005) Report from the I.R.F.S.I.N.T.S.W. principles for characterizing the potential human health effects from exposure to nanomaterials: elements of a screening. Toxicology 2:1–35

Park HM, Li X, Jin CZ, Park CY, Cho WJ, Ha CS (2002) Preparation and properties of biodegradable thermoplastic starch/clay hybrids. Macromol Mater Eng 287:553–558

Patil SA (2009) Economics of agriculture poverty: nano-bio solutions. Indian Agricultural Research Institute, New Delhi

Pérez-de-Luque A, Rubiales D (2009) Nanotechnology for parasitic plant control. Pest Manag Sci 65:540–545

Perni S, Piccirillo C, Pratten J, Prokopovich P, Chrzanowski W, Parkin IP, Wilson M (2009) The antimicrobial properties of light-activated polymers containing methylene blue and gold nanoparticles. Biomaterials 30:89–93

Peters RJ, Bouwmeester H, Gottardo S, Amenta V, Arena M (2016) Nanomaterials for products and application in agriculture, feed and food. Trends Food Sci Technol 54:155–164

Prasad R, Kumar V, Prasad KS (2014) Nanotechnology in sustainable agriculture: present concerns and future aspects. Afr J Biotechnol 13:705–713

Prasanna BM (2007) Nanotechnology in agriculture. I.A.R.I, New Delhi, pp 111–118. ICAR National Fellow, Division of Genetics

Prashanth P, Raveendra R, Krishna RH, Ananda S, Bhagya N, Nagabhushana B, Lingaraju K, Naika HR (2015) Synthesis, characterizations, antibacterial and photoluminescence studies of solution combustion-derived α-Al2O3 nanoparticles. J Asian Cera Soc 3:345–351

Priester JH et al (2012) Soybean susceptibility to manufactured nanomaterials with evidence for food quality and soil fertility interruption. Proc Natl Acad Sci USA 0937:E2451–E2456

Qian K, Shi T, Tang T, Zhang S, Liu X, Cao Y (2011) Preparation and characterization of nano-sized calcium carbonate as controlled release pesticide carrier for validamycin against *Rhizoctonia solani*. Microchim Acta 173:51–57

Qu X, Brame J, Li Q, Alvarez PJ (2012) Nanotechnology for a safe and sustainable water supply: enabling integrated water treatment and reuse. Acc Chem Res Acta 46(3):834–843

Racuciu M, Creanga DE (2006) TMA-OH coated magnetic nanoparticles internalized in vegetal tissue. Rom J Phys 52(3–4):395–402

Rajakumar G, Rahuman AA, Roopan SM, Khanna VG, Elango G, Kamaraj C, Zahir AA, Velayutham K (2012) Fungus-mediated biosynthesis and characterization of TiO2 nanoparticles and their activity against pathogenic bacteria, Spectrochim. Acta Mol Biomol Spectrosc 91:23–29

Raliya R, Nair R, Chavalmane S, Wang WN, Biswas P (2015) Mechanistic evaluation of translocation and physiological impact of titanium dioxide and zinc oxide nanoparticles on the tomato (*Solanum lycopersicum* L.) plant. Metallomics 12:1584–1594

Rangaraj S, Venkatachalam R (2017) A lucrative chemical processing of bamboo leaf biomass to synthesize biocompatible amorphous silica nanoparticles of biomedical importance. Appl Nanosci 7:145–153

Ren G, Hu D, Cheng EW, Vargas-Reus MA, Reip P, Allaker RP (2009) Characterisation of copper oxide nanoparticles for antimicrobial applications. Int J Antimicrob Agents 33:587–590

Rizal G, Karki S, Thakur V, Chatterjee J, Coe RA, Wanchana S, Quick WP (2012) Towards a C4 rice. Asian J Cell Biol 7:13–31

Roberts TL (2009) The role of fertilizer in growing the world's food. Better Crops Plant Food 93:12–15

Roy A, Gauri SS, Bhattacharya M, Bhattacharya J (2013) Antimicrobial activity of CaO nanoparticles. J Biomed Nanotechnol 9:1570–1578

Sage RF, Sage TL, Kocacinar F (2012) Photorespiration and the evolution of C_4 photosynthesis. Annu Rev Plant Biol 63:19–47

Saharan V, Mehrotra A, Khatik R, Rawal P, Sharma SS, Pal A (2013) Synthesis of chitosan based nanoparticles and their in vitro evaluation against phytopathogenic fungi. Int J Biol Macromol 62:677–683

Sasson Y, Levy-Ruso G, Toledano O, Ishaaya I (2007) Nanosuspensions: emerging novel agrochemical formulations., 2007, In: Ishaaya I, Nauen R, Horowitz AR, editors. Insecticides design using advanced technologies Netherlands: Springer-Verlag. p. 1-32. Schaad NW, Opgenn.

Sawai J (2003) Quantitative evaluation of antibacterial activities of metallic oxide powders (ZnO, MgO and CaO) by conductimetric assay. J Microbiol Meth 54:177–182

Sawai J, Yoshikawa T (2004) Quantitative evaluation of antifungal activity of metallic oxide powders (MgO, CaO and ZnO) by an indirect conductimetric assay. J Appl Microbiol 96:803–809

Scholes GD, Sargent EH (2014) Bioinspired materials: boosting plant biology. Nat Mater 13 (4):329–331

Sharif Hossain AB, Ibrahim NA, Al Eissa MS (2016) Nano-cellulose derived bioplastic biomaterial data for vehicle bio-bumper from banana peel waste biomass. Data Brief 8:286–294

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019) Growth, yield and quality of cluster bean (*Cyamopsis tetragonoloba*) as influenced by integrated nutrient management under alley cropping system. Indian J Agricul Sci 89(11):1876–1880

Shevchenko S, Burkhardt M, Sheval EV, Natashina UA, Grosse C, Nikolaev AL, Gopin AV, Neugebauer U, Kudryavtsev AA, Sivakov V, Osminkina LA (2017) Antimicrobial effect of biocompatible silicon nanoparticles activated using therapeutic ultrasound. Langmuir 33 (10):2603–2609

Sheykhbaglou R, Sedghi M, Shishevan MT, Sharifi RS (2010) Effects of nano-iron oxide particles on agronomic traits of soybean. Notulae Scientia Biologicae 2(2):112–113

Silva Mdos S, Cocenza DS, Grillo R, de Melo NF, Tonello PS, de Oliveira LC, Cassimiro DL, Rosa AH, Fraceto LF (2011) Paraquat-loaded alginate/chitosan nanoparticles: preparation, characterization and soil sorption studies. J Hazard Mater 190:366–374

Silvestry-Rodriguez N, Sicairos-Ruelas EE, Gerba CP, Bright KR (2007) Silver as a disinfectant. Springer, Reviews of Environmental Contamination and Toxicology, pp 23–45

Singh Nee Nigam P, Pandey A (2009) In: Nigam PS, Pandey A (eds) Biotechnology for agro-industrial residues utilisation. Springer, Dordrecht, p 466

Singh R, Singh R, Singh D, Mani JK, Karwasra SS, Beniwal MS (2010) Effect of weather parameters on Karnal bunt disease in wheat in Karnal region of Haryana. J Agrometeorol 12:99–101

Sirelkhatim A, Mahmud S, Seeni A, Kaus NHM, Ann LC, Bakhori SKM, Hasan H, Mohamad D (2015) Review on zinc oxide nanoparticles: antibacterial activity and toxicity mechanism. Nano-Micro Lett 7(3):219–242

Smetana AB, Klabunde KJ, Marchin GR, Sorensen CM (2008) Biocidal activity of nanocrystalline silver powders and particles. Langmuir 24:7457–7464

Sondi I, Salopek-Sondi B (2004) Silver nanoparticles as antimicrobial agent: a case study on E. coli as a model for gram-negative bacteria. J Colloid Interf Sci 275(1):177–182

Song MR, Cui SM, Gao F, Liu YR, Fan CL, Lei TQ, Liu DC (2012) Dispersible silica nanoparticles as carrier for enhanced bioactivity of chlorfenapyr. J Pestic Sci 37:258–260

Stephenson GR (2003) Pesticide use and world food production: risks and benefits. ACS Publications, Washington, DC

Subramanian KS, Tarafdar JC (2011) Prospects of nanotechnology in Indian farming. Indian J Agric Sci 81:887–893

Sun C, Shu K, Wang W, Ye Z, Liu T, Gao Y, Zheng H, He G, Yin Y (2014) Encapsulation and controlled release of hydrophilic pesticide in shell cross-linked nanocapsules containing aqueous core. Int J Pharm 463:108–114

Sunkar S, Valli Nachiyar C (2012) Microbial synthesis and characterization of silver nanoparticles using the endophytic bacterium Bacillus cereus: a novel source in the benign synthesis. Glob J Med Res 12:43–49

Sushil SN (2016) Emerging issues of plant protection in India. In: Natural resource management: ecological perspectives. International conference, SKUAST, Jammu

Syngouna VI, Chrysikopoulos CV (2017) Inactivation of MS2 bacteriophage by titanium dioxide nanoparticles in the presence of quartz sand with and without ambient light. J Colloid Interface Sci 497:117–125

Tepe O, Dursun AY (2014) Exo-pectinase production by *Bacillus pumilus* using different agricultural wastes and optimizing of medium components using response surface methodology. Environ Sci Pollut Res In 21(16):9911–9920

Thakur S, Thakur T, Kumar R (2018) Bio-nanotechnology and its role in agriculture and food industry. J Mol Genet Med 12:1–5

Torney F (2009) Nanoparticle mediated plant transformation. In: Emerging technologies in plant science research, Interdepartmental plant Physiol major fall seminar series physics. UBC Press, Vancouver, p 696

Torney F, Trewyn BG, Lin VS, Wang K (2007) Mesoporous silica nanoparticles deliver DNA and chemicals into plants. Nat Nanotechnol 2(5):295–300

Vamvakaki V, Chaniotakis NA (2007) Pesticide detection with a liposome-based nanobiosensor. Biosens Bioelectron 22:2848–2853

Viirlaid E, Riiberg R, Mäeorg U, Rinken T (2009) Glyphosate attachment on aminoactivated carriers for sample stabilization and concentration. Agron Res 13:1152–1159

Vijayakumar PS, Abhilash OU, Khan BM, Prasad BLV (2010) Nanogold-loaded sharp-edged carbon bullets as plant-gene carriers. Adv Funct Mater 20:2416–2423. https://doi.org/10.1002/adfm.200901883

Wanekaya AK, Chen W, Myung NV, Mulchandani A (2006) Nanowire-based electrochemical biosensors. Electroanalysis 18(6):533–550

Wang Z, Wei F, Liu SY, Xu Q, Huang JY, Dong XY, Yu JH, Yang Q, Zhao YD, Chen H (2010) Electrocatalytic oxidation of phytohormone salicylic acid at copper nanoparticles-modified gold electrode and its detection in oilseed rape infected with fungal pathogen *Sclerotinia sclerotiorum*. Talanta 80:1277–1281

Wang H, Kou X, Pei Z, Xiao JQ, Shan X, Xing B (2011) Physiological effects of magnetite (Fe3O4) nanoparticles on perennial ryegrass (*Lolium perenne* L.) and pumpkin (*Cucurbita mixta*) plants. Nanotoxicology 5(1):30–42

Wang Y, Cui H, Sun C, Zhao X, Cui B (2014) Construction and evaluation of controlled-release delivery system of Abamectin using porous silica nanoparticles as carriers. Nanoscale Res Lett 9:2490

Wang L, Hu C, Shao L (2017) The antimicrobial activity of nanoparticles: present situation and prospects for the future. Int J Nanomedicine 12:1227–1249. https://doi.org/10.2147/IJN.S121956

Wibowo D, Zhao CX, Peters BC, Middelberg AP (2014) Sustained release of fipronil insecticide in vitro and in vivo from biocompatible silica nanocapsules. J Agric Food Chem 62:12504–12511

Xue H, Chen Y, Liu X, Qian Q, Luo Y, Cui M, Chen Y, Yang DP, Chen Q (2018) Visible light-assisted efficient degradation of dye pollutants with biomass-supported TiO2 hybrids. Mater Sci Eng C 82:197–203

Yadav GS, Lal R, Meena RS (2020) Vehicular traffic effects on hydraulic properties of a Crosby silt loam under a long-term no-till farming in Central Ohio, USA. Soil and Till Res 202:104654

Yang FL, Li XG, Zhu F, Lei CL (2009) Structural characterization of nanoparticles loaded with garlic essential oil and their insecticidal activity against *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). J Agric Food Chem 57:10156–10162

Yao KS, Li SJ, Tzeng KC, Cheng TC, Chang CY, Chiu CY, Liao CY, Hsu JJ, Lin ZP (2009) Fluorescence silica nanoprobe as a biomarker for rapid detection of plant pathogens. Adv Mater Res 79(82):513–516

Yehia RS, Ahmed OF (2013) In vitro study of the antifungal efficacy of zinc oxide nanoparticles against *Fusarium oxysporum* and *Penicilium expansum*. Afr J Microbiol Res 7:1917–1923

Zamani L, Mirjalili BBF, Zomorodian K (2014) Synthesis of benzimidazoles in the presence of nano-TiCl4. SiO2 as antifungal agents and tautomerism theoretical study of some products. Synthesis 62:3

Zhang H, Li Q, Lu Y, Sun D, Lin X, Deng X (2005) Biosorption and bioreduction of diamine silver complex by Corynebacterium. J Chem Technol Biotechnol 80:285–290

Zhang X, Zhang J, Zhu KY (2010) Chitosan/double-stranded RNA nanoparticles-mediated RNA interference to silence chitin synthase genes through larval feeding in the African malaria mosquito (Anopheles gambiae). Insect Mol Biol 19:683–693

Zhang J, Li M, Fan T, Xu Q, Wu Y, Chen C, Huang Q (2013) Construction of novel amphiphilic chitosan copolymer nanoparticles for chlorpyrifos delivery. J Polym Res 20:107

Solar Radiation and Nitrogen Use Efficiency for Sustainable Agriculture

6

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Abstract

The growth rate of each plant (dry matter accumulation rate) mainly depends on sun's energy interception (electromagnetic radiation) and leaf nitrogen (N) content for carbon assimilation. Radiation use efficiency (RUE) is an essential factor utilized by many of the simpler plant growing models to simulate the process of photosynthesis, i.e., conversion of light energy and carbon dioxide (CO_2) to plant biomass. The productivity of crop is limited by its thermodynamic properties and the sustained climate of both the plant and its ecosystem. The application of industrial N fertilizers in agricultural production has enhanced the crop yield two to three times more in the last century to meet the rising worldwide population demands. This chapter is focused on the efficient use of solar radiations and integrated N management to enhance crop nitrogen production, taking into account soils, increased utilization of fertilizer, and better crop management strategies. Therefore, optimizing the efficiency of radiations and nitrogen use in agricultural systems is critical and yet to be explored.

Keywords

Biomass · Canopy size · Crop biomass · Light interception · Nitrogen remobilization · Nitrogen remodeling · Nitrogen use efficiency · Radiation use efficiency

Abbreviations

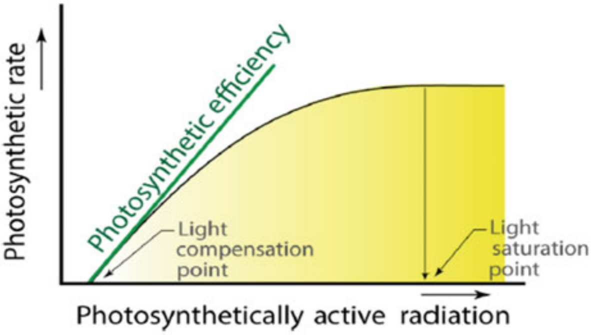
BMPs	Best management practices
C	Carbon
C/N	Carbon/nitrogen
C_3	Plants in which the primary CO_2 acceptor is 3-carbon compound
C_4	Plants in which the primary CO_2 acceptor is 4-carbon compound
CO_2	Carbon dioxide
GIS	Geographical information systems
gm^{-2}	Grams per meter square
gMJ	Gram megajoule
$\mu molm^{-2}\ s^{-1}$	Micromole per meter square per second
IR	Infrared
LAI	Leaf area index

N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NIR	Near-infrared
NO_3	Nitrate
NUE	Nitrogen use efficiency
PAR	Photosynthetically active radiation
RUE	Radiation use efficiency
UV	Ultraviolet radiations
VPD	Vapor pressure deficit

6.1 Introduction

In the last century, improvements in light-energy collection and conversion were a major component to the improvement of crops. The productivity of crop is limited by its thermodynamic properties and the sustained climate of both the plant and its ecosystem. By the process of photosynthesis, carbon dioxide (CO_2) and water combine in chloroplast and form simple sugars. However, the factors which affect the available sunlight on the plant canopy's floors make this simple process complex. This can be seen from the light reaction diagram showing how the available sunlight (irradiance) is connected to the photosynthesis rate (Fig. 6.1). The effectiveness of radiation use efficiency (RUE) seems to be very important in assessing the development of plants focused on resource capture and productivity. It is confirmed as the crop biomass of the overall solar irradiance or photosynthetically active radiation (PAR), which is captured by the canopy. Excellent reviews (Sinclair and Muchow 1999a, b) and articles (Monteith 1977) have been focused on the concept of radiation capture and efficiency and its application for assessing relative crop performances under diverse management practices and environmental conditions. It generally considers productivity as the outcome of a total assimilation rate by area of leaf and total surface area of the leaf. The ideas are conceptually accurate but include some drawbacks, as discussed by Monteith (1994) and probably by Sinclair and Muchow (1999a, b) in overly critical tones. The standard method for

Fig. 6.1 Photosynthesis reaction to the photosynthesis of light-saturation level



evaluating crop production relying on radiation absorption and photosynthetic RUE considers a canopy instead of being a representative region of the leaf, as shown by the net absorption rate. The increased erect nature of leaves, for example, has allowed a rise in the unit area of the leaf, allowing for highly efficient crop canopy absorption by radiation. Input management has also improved the conversion rate: the use of fertilizers improves the leaf surface and the net photosynthetic rate. The leaf area index (LAI) serves as an intermediary variable for the assessment of the detection and distribution of radiation across the canopy rather than as a focal point. Hammer et al. (2004) argued that abstractions should be made at a useful aggregate level for plant communities to study.

Analysis of photosynthetic radiations and the RUE system may be represented as follows:

$$\mathrm{PB} = \mathrm{RUE}\, f_{\mathrm{is}}\, \mathrm{S_t} \tag{1A}$$

$$\mathrm{Y_c} = \mathrm{HI_{ob}}\, \mathrm{RUE}\, f_{\mathrm{is}}\, \mathrm{S_t} \tag{1B}$$

where PB is provided by plant biomass (Grams per meter square—gm^{-2}), radiation use efficiency (RUE) by crop parameter (Gram mega joule—gMJ^{-1}), $\mathrm{S_t}$ of overall received solar radiations ($\mathrm{MJ\ m}^{-2}$), f_{is} is the fraction of the incident solar irradiance that is absorbed into the canopy, $\mathrm{Y_c}$ is the yield of crop (gm^{-2}), and $\mathrm{HI_{ob}}$ represents the ratio of collectability of organic biomass or harvest index of organic biomass (normally computed from shoot biomass for cereal grain crops or of total tuber and root production biomass). Solar radiations (S_t) represent the fundamental basis for the calculation of RUE. Photosynthetically active radiation (PAR) might be utilized to calculate the amount of solar radiations and serves as the basis for RUE ($\mathrm{RUE_{PAR}}$), a wavelength in the visible spectrum range that drives photosynthesis (almost, all of captured power in PAR range), dissipates in the form of heat, might used certainly and preferable when incident PAR is accessible.

Warren Wilson (1967) introduced the concept of RUE system four decades earlier (Eq. 1A and 1B). This method has been used extensively for modeling biomass generation (Jones et al. 1998) and for analyzing agronomical experiments (Sadras et al. 2005; Wang et al. 2015). Although the reports documented on RUE is comprehensive, some papers may suggest theories, experiments, as well as modeling so as to obtain knowledge of the RUE and growth variability based on the study of hypotheses (Hall et al. 1995). Radiation use efficiency values are commonly reflections of the events, thereby the concept remains uninvestigated how this occurred, which render the system's functioning incomplete. Also, RUE perception is affected by environmental conditions, stress, canopy design, and other external factors.

However, many of these characteristics of crop plants have already been configured or near to optimization (Horton 2000; Sheehy 2000), and have played a crucial role in creating green revolutions (nitrogen response, harvest index, canopy size, and architecture). The problem, therefore, remains whether the production rate of crop biomass is equally optimized. It may be suggested that yield growth is related to improve the overall biomass production, but certain studies show that yield and biomass are not significantly associated with improvement (Calderini et al. 1995; Meena et al. 2016a, 2017b). Traditional crops physiology tells us that the overall accumulated dry biomass is strongly and positively related to the cumulative solar radiation intercepted.

Nitrogen (N) is a key component in several bio-molecules, such as peptides and proteins that perform life chemistry, nucleic acids that encode genome information with other structural and functional roles. The minimum amount of N accessible to the primary plants and several other autotrophic speciess in the natural environment and agricultural production systems limits their production and efficiency (Elser et al. 2007). In many agricultural systems, tremendous exploitation of industrial N fertilizers alleviated the N limitations and during the middle of the twentieth century, it led to "Green Revolution." The comprehensive use of N fertilizers has enhanced by more than 100 million tons, but with an exponential increase in population (doubling from 1961 to 2009), the cereal grain production has approximately tripled (Godfray et al. 2010). The excessive utilization of fertilizers has increased the nitrogen flow by a land-based N cycle in the biosphere (Canfield et al. 2010), and the depletion of reactive-nitrogen due to crop production systems, harmed the human health and habitats and had an effect on climate change (Michael Beman et al. 2005; Sutton et al. 2011; Meena et al. 2018b, 2020b).

In the present scenario fertilizer utilization potential is likely to be unsustainable (Rockström et al. 2009). Nonetheless, it is estimated that N fertilizer use would be increased to meet the rising worldwide population demands (Ladha and Chakraborty 2016). However, there is space for optimization, since different approaches have been found to decrease the quantity for grain, feed, fiber, and fuel for N fertilizers as required by the agricultural system, globally. Among these are: more sustainable use of leguminous products, which may add N to the agricultural production systems through biological symbiotic N fixation process (Biswas and Gresshoff 2014); enhanced field-scale nitrogen use efficiency (NUE) by improved fertilizer type management, amount and timing, and better crop density management, water, planting and harvest periods, additional nutrient requirements, and pest management system for ideal crop yield (Chu et al. 2016).

The utilization of any fertilizer, inorganic as well as organic, will pose an environmental hazard if it is misused. The mineral fertilizers provide 192 metric tons as input to agricultural land, out of which N contributes 109 metric tons (Fig. 6.2a), growing global population; probably 7.9–10.5 billion by the year 2050, and fiber, food, feed, and energy requirements (FAO, Washington DC, United States 2019). By region, Asia represented 57% of world agricultural use of fertilizers, America 26%, Europe 12%, Africa 3%, and Oceania 2%. (Fig. 6.2b). While large numbers of N fertilizers have been used worldwide, the productivity of nitrogen fertilizers utilized by plants in cultivated lands is comparatively small, varying from 25–50%of the applied N (Chien et al. 2016). Low efficiency of N consumption may lead to a concerning environmental, economic, and conservation status and indicates an urgent need to increase N output (NUE) of fertilizers. In addition to increasing N consumption, farmers are concerned with a sharp increase in

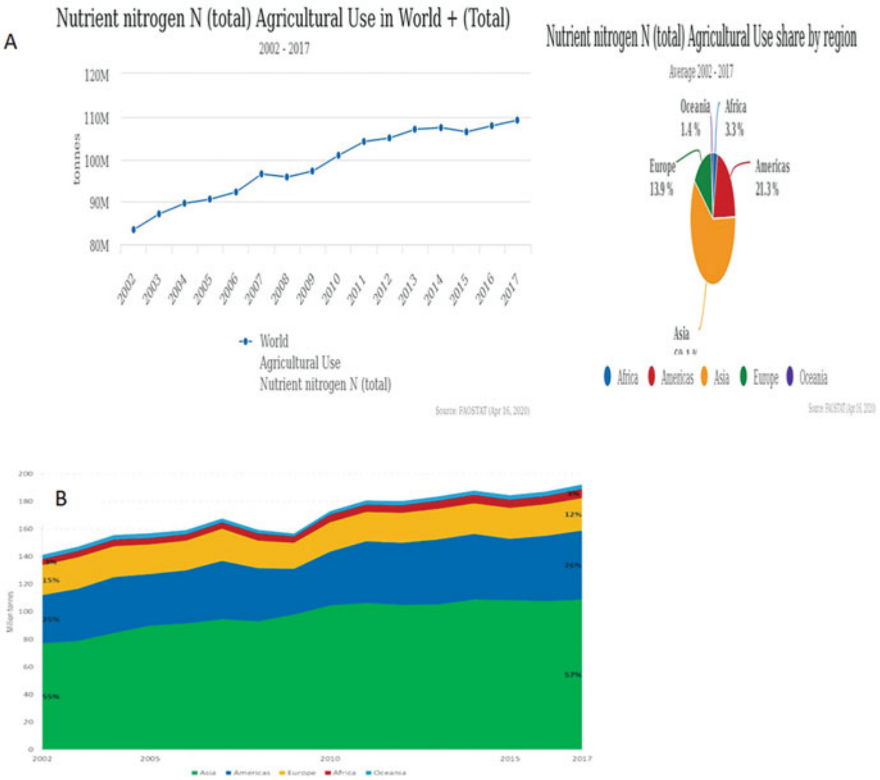


Fig. 6.2 (**a**) Global fertilizer demand, and three major crop nutrients (phosphates, nitrogen, and potash) projections during 2015–2019 session (**b**) Projections on global and regional nitrogen fertilizer requirement during 2015–2019 session. (Adapted, FAO 2019)

fertilizer costs. Therefore, in crop production, the increased usage and expense of N fertilizers is concerning. Enhanced NUE has the ability, with negligible environmental impacts, to maximize returns and yields and benefit by 18.75 US dollars per acre (Zoubek and Nygren 2008).

Our aim here is to summarize the use of RUE and leaf N mobilization in the agricultural, breeding, and modeling study of crop growth. There are also discussions of constraints that can restrict the utility of the RUE. We will also discuss various N-use output (NUE) control factors and methods to enhance NUE in agriculture by reducing losses in the environment.

6.2 Photosynthetic Radiations-Use Efficiency for Crops Biomass Accumulation

Radiation use efficiency is easy to determine on the ground. The intercepted radiations and crop biomass accumulation at time intervals are required for estimation of RUE, which is acceptable for precise and efficient measurements of absorbed radiation and accretion of biomass. Eq. (1A and 1B) shows that RUE is the ratio of accumulation of biomass to the interception of radiation during the period considered. Radiations-use efficiency calculations are commonly derived as the slope of linear regression relationship among the accumulated matter and intercepted cumulative radiation for a certain period to minimize sampling variability. Sinclair and Muchow (1999a, b) give a complete analysis of abiotic factors, which help to determine unsureness and deviations in RUE. Soil and crop variations are significant sources of uncertainties. The relationship between various levels of fertility and cultivars can be analyzed to calculate the RUE to assess energy efficiency and appropriate fertilization practices to maximize productivity (Satpal Tokas et al. 2018). It may be difficult to collect adequate samples to quantify biomass with appropriate statistical reliability while reducing interruptions in crop growth. Ideally, radiation detection assessment should be performed continuously over the whole logistically and financially difficult period. However, accurate radiation detection estimates can be derived by using independent measurements. To provide accurate routine monitoring of the radiation interception, a field approach should consider carefully, the regularity of estimation, day time, and location of the sensor to be placed. The measurements of radiation intercept in the canopy with defined rear architecture if the sun would be at the same altitude as the line can, may underestimate regular radiations absorption by 15% or above according to line dimensions. There are easy and straightforward models of radiation transfer mechanism that enables this fault to be corrected in crop rows (Campbell and van Evert 1994).

6.2.1 Solar and Photosynthetically Active Radiation-Based Resource Use Efficiency

Radiations from sun penetrating the surface of earth comprise around 3–4% of ultraviolet rays that lies in the wavelength band at ultraviolet radiations (UV) $<$ 0.4 μm and about the same proportion in PAR at 0.4–0.7 μm and the infrared (IR) at $>$0.7 μm wavelength. The majority of IR radiations reaches the surface is close to near-infrared radiations (NIR) at $>$0.7–1.4 μm. UV/PAR radiations are greater, when these rays are almost diffused, however, due to interactions between turbidity, solar elevation, and air cloudiness; it is very much difficult to predict the precise global photoactive radiation spectral efficiency (Monteith and Unsworth 2008). The PAR/St ratio is normally 0.5, while Howell et al. (1983) reported a ratio closer to 0.45. It is convenient to distinguish the solar spectrum in NIR/PAR, as these two wavebands differ greatly in the optical properties of the leaf surface. The radiation absorptions quantified with total solar radiations detecting sensory system provide

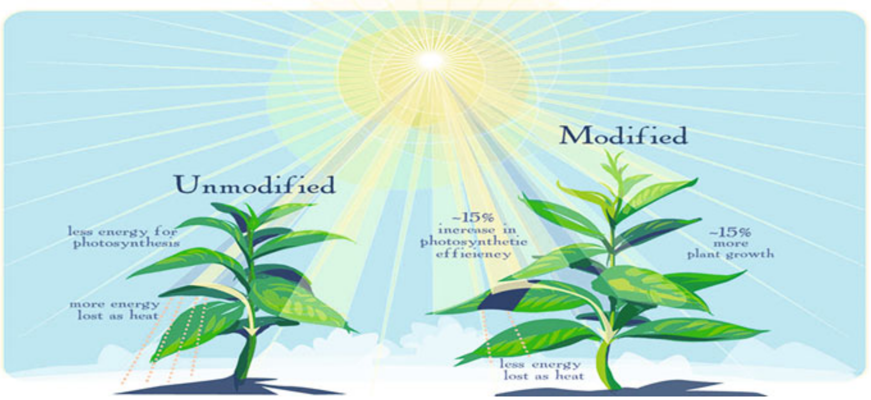


Fig. 6.3 The effect of photosynthetically active radiation in clear-sky days (Source: University of Illinois at Urbana-Champaign)

several absorbed fractions due to single leaf blade absorption (α) and transmittal absorption of both PAR and NIR; $\alpha_{NIR} \sim 0.15$ and $\alpha_{PAR} \sim 0.85$ for a leaf blade (Ross 1975). Radiation proportion deflected via a canopy (τ) mainly relies on both PAR and NIR's relative absorption and reflections. The UV balance was typically ignored because of the small participation of ultraviolet rays to the total spectrum of photoactive radiations. As the UV is indeed greater to PAR, leaf elements may act as a medium around the particular wavelength. Nevertheless, UV radiation is quite more intense than PAR in clear-sky days (Fig. 6.3).

The absorption of the canopy is superior to the absorbability of a single leaf, since the beam transmitted by a leaf may also counter-interact with the remaining portion of the leaf blade. The relationship between UV and PAR on top of and beneath the canopy is fairly similar, but radiation reaching the ground has been intensified by NIR relative to incoming radiations due to effective absorption of PAR and UV rays by foliage. The exact accumulation ratio depends on the design and size of the canopy; thus, converting RUE_{PAR} to RUE_S is no trivial task. Bonhomme (2000) traced out some common errors in the literature during such exchange and studied the dissimilarities in the transmission coefficients due to various (temperate-based and equatorial-based) radiation dynamics, canopy sizes, and plant geometry. Campbell and van Evert (1994) also reported similar calculations. Goudriaan (1977) demonstrated a sensible approximation of the radiation dispersal in crop canopies from the exponential model. After Goudriaan, the radiation portion of each waveband disseminated via. Canopy (τ) was relatively well defined by $\tau = \exp. (-\alpha^{0.5}{}_{kb}\mathrm{LAI})$, where the sum of the product $\alpha^{0.5}{}_{kb}$ is extinguishing coefficient (k) for every wavelength, while k_b is extinguishing coefficient used ($\alpha = 1$). Regular k can be determined, providing that the everyday radiation integral is closely aligned with dispersing photo-radiation transmission (Campbell and van Evert 1994). The k_S range from 0.35–0.60, with most k_s approximately 0.44–0.50, k_{PAR} 0.45–0.9, for vertical and horizontal angle distributions (Kemanian et al. 2004). For a constant distribution of the leaf inclination, k varies with leaf area index; thus, the constant k during cultivation period signifies progressive distribution transition of the sheet angle. If the everyday k_{PAR} is accessible, everyday k_s is estimated by $k_s = 0.62\ k_{PAR}$ (0.86) and $k_{PAR} = 1.62\ k_s$ (1.16). Nevertheless, solar radiation interception is evaluated separately, dependent on both PAR and NIR interception. The efficiency of photosynthetic radiations may vary among different plant species, for example, maximum RUE_S in C_3 (plants in which the primary CO_2 acceptor is 3-carbon compound) (1.4 gMJ^{-1}) and C_4 plants (plants in which the primary CO_2 acceptor is 4-carbon compound) (2.0 gMJ^{-1}) species were reported by Monteith (1977, 1978). Total RUEs for different crop species are summarized in Table 6.1.

This is a summary and an update on Sinclair and Muchow's review (1999a, b). Unless otherwise indicated, shoot biomass is only taken into account. The variations between the species may vary, particularly from perennial to annual, developing, and phenological conditions (Brown et al. 2006)

Photosynthetic crop use efficiency for biomass accumulation could be optimized for the energy expense of biosynthesis in crops with higher oil or protein concentration, which is largely dependent on the newly accumulated biomass, oil or protein content as well as the source of N. Sinclair and Horie (1989) have calculated highest RUE in maize which is to be around 1.8 gMJ^{-1}. Kiniry et al. (1999) observed RUE-equivalent of switchgrass to *Eriochloa polystachya* (2.0–2.4 gMJ^{-1}), without even taking into account its origin and by the same study, two factors were higher than three in other perennial grasses (C_4) (the RUE overestimation may have been triggered by a small underestimate of radiation interception). The RUE of sorghum used for feed purpose sorghum tends to be marginally less than other C_4 annual crop species, such as maize or millet, and sweet sorghum tends to be one among the maximum possessing RUE. The maximum RUE for C_3 crops was recorded for potato (Manrique et al. 1991), sugar beets (Malnou et al. 2008), mainly consistent with crops that mostly accumulate simplicity of total sugars, starch, and low oil or protein content. The cereals grown during winter such as wheat, barley, and oat exhibited values close to 1.7 gMJ^{-1}, which was about 15% lesser than the average estimates for C_4 crop species. On the basis of reported literature, the rice and non-grass non-legume crops that grow in summer, possibly except for sunflower, have slightly lower RUE. Due to the loss of CO_2 in photorespiration process during the summers, this may represent lower photosynthetic efficiency. The C_3 perennial grasses have less RUE than C_3 annual grasses, but their differences are likely to be marginal when considering the distribution of biomass to underlying organs. Legumes show lower RUE than other C_3 plants. The explanation that RUE is less in these plants is not completely understood; a sink control may partially regulate RUE

6.2.2 Factors Affecting Photosynthetic Radiation Use Efficiency

Although the definition for RUE is basic, literature does not fully understand or treat the plant, atmospheric, and management factors that influence RUE. Radiation use

Table 6.1 Photosynthetic crop use efficiency of different crop species

Crop	Categories of crops	C_3/C_4 types	RUE values (gMJ^{-1})	References
Orchardgrass (*Dactylis glomerata*)	Perennial grass	C_3	1.1	Duru et al. (1995)
Phalaris minor	Perennial grass	C_3	1.4–1.6	Kätterer et al. (1998)
Ryegrass (*Lolium perenne*)	Perennial grass	C_3	1.7–2.3	Akmal and Janssens (2004)
Fescue (*Festuca arundinacea*)	Perennial grass	C_3	1.3	Duru et al. (1995)
Wheat (*Triticum aestivum*)	Annual grass	C_3	1.6–1.7	Kemanian et al. (2004)
Rice (*Oryza sativa*)	Annual grass	C_3	1.2–1.5	Mitchell et al. (1998)
Oat (*Avena sativa*)	Annual grass	C_3	1.2–1.7	Muurinen and Peltonen Sainio (2006)
Barley (*Hordeum vulgare*)	Annual grass	C_3	1.5–1.7	Kemanian et al. (2004)
Cotton (*Gossypium* spp.)	Oil crop	C_3	1.5	Rosenthal and Gerik (1991)
Sunflower (*Helianthus annuus*)	Oil crop	C_3	1.7–2.0	Trapani et al. (1992)
Canola (*Brassica napus*)	Oil crop	C_3	1.3–1.5	Marcos (2000)
Safflower (*Carthamus tinctorius*)	Oil crop	C_3	1.3–1.6	Marcos (2000)
Flax (*Linum usitatissimum*)	Oil crop	C_3	1.7	D'Antuono and Rossini (1995)
Switch grass (*Pancium virgatum*)	Perennial grass	C_4	2.0–2.4	Kiniry et al. (1999)
Miscanthus (*Miscanthus giganteus*)	Perennial grass	C_4	2.0	Beale and Long (1995)
Sugarcane (*Saccharum offiicinarum*)	Perennial grass	C_4	1.7–1.8	Muchow et al. (1997)
Sorghum (*Sorghum bicolor*)	Annual grass	C_4	1.7–1.8	Kiniry et al. (1998)
Pearl millet (*Pennisetum glaucum*)	Annual grass	C_4	1.9	Van Oosterom et al. (2002)
Maize (*Zea mays*)	Annual grass	C_4	2.0	Lindquist et al. (2005)
Sweet sorghum	Annual grass	C_4	1.9–2.5	Matrorilli et al. (1995)
Alfalfa (*Medicago sativa*)	Legume crop	C_3	1.1	Brown et al. (2006)
Peas (*Pisum sativum*)	Legume crop	C_3	1.5	Lecoeur and Ney (2003)
Soybean (*Glycine max*)	Legume crop	C_3	1.0 1.1	Rochette et al. (1995)

(continued)

Table 6.1 (continued)

Crop	Categories of crops	C_3/C_4 types	RUE values (gMJ^{-1})	References
Peanuts (*Arachis hypogaea*)	Legume crop	C_3	1.2	Kiniry et al. (2005)
Garlic (*Allium sativum*)	Other non-grain storage crop	C_3	1.6–1.8	Rizzalli et al. (2002)
Potato (*Solanum tuberosum*)	Other non-grain storage crop	C_3	1.6–1.7	Sinclair and Muchow (1999a, b)
Sugar beet (*Beta vulgaris*)	Other non-grain storage crop	C_3	1.9	Malnou et al. (2008)

The results are expressed on the shoot biomass basis and photosynthetic solar radiations and should have been considered suitable for 360–380 $\mu molmol^{-1}$ atmospheric CO_2

efficiency, like gross photosynthesis and net photosynthetic rate, maybe influenced via several external environmental aspects like temperature, relative humidity, radiations, or by plant's internal factors like sunset control, nutrition, and water status, oncogenicity, and control of the source-sink relationship. Once introduced into a canopy, the responses at the leaf basis are damped or tamped and the RUE reactions to this type of influences are thus moderated. Besides, canopy levels, particularly canopy architectures, might possess a major influence on RUE. The influence of the management variables should also be considered as plant environment managements or physiological factors influencing RUE. The plant density or date of seeding does not have a pronounced effect on RUE or any different method. They may function by several plant's physiological mechanisms separate from the management practices.

6.2.2.1 Canopy Size

With the proportion of non-saturated irradiance LAI activities, RUE is expected to increase, with an improvement in LAI. For annual crops, this impact should be evident when both LAI and f_i are low during the first phases of development. The effect was initially suggested in winter barley and wheat (Gallagher and Biscoe 1978) but specifically investigated in sunflower (Trapani et al. 1992). Artificial radiation variability over the canopy is quite inexistent, but it may be possible to manipulate natural irradiance at the leaf surfaces by adjusting the distribution of the leaf angle. Further work has been carried out on the light dispersion of a large portion of the input radiation from some cereals that might possess lengthy awns, e.g., barley, which may absorb and distribute the RUE of the underlying foliage. The articles written by Duncan et al. (1967) and Loomis and Williams (1969) were the classical references to canopy photosynthesis and, through RUE implications. Based on the above discussion, sunlight, irradiance, or radiation beams are useful in situations, where the sun's elevation or beam portion is high, with vertical angles (sphere angles distribution that is still on the vertical side). Under conditions of low LAI, without water and nutritional stress, crops can use the maximum amount of radiation available to intercept; thus, horizontal, non-overlapping leaves are desirable. The ideotype cultivation would, therefore, have a canopy and after emergence primarily horizontal in position and progressively change to upright with high LAI levels. Several researchers would have identified oat and barley genotypes similar to this behavior. The benefit of vertical canopies may not be to raise RUE under water stress conditions but to decrease radiation detection and thereby, the energy load.

Though canopy structure is a necessary halt when addressing canopy photosynthetic and radiation use efficiency (Reynolds et al. 2000; Long et al. 2006), while modeling the canopy design, care should be taken because of the often confused or ambiguous “vertical canopy” and “vertical angle distribution” for the leaves. Vertical canopy is quietly used to explain vertical leaf canopy on upper edge of the canopies, which turns progressively horizontally into a radiating leafy Yucca plant (Long et al. 2006) towards the bottom of the profile. Nevertheless, it can retain fairly high RUE, when effectively interfering incident radiation interceptions, making it more preferred than canopies with isotopically and vertical angle distributions. The leaf pattern is hardly vertical but is highly anisotropic. In general, while canopies optimized for RUE are measurable, there may be certain limitations in trait handling, as stated by Rasmusson (1991), for barley, including canopy design due to pleiotropism and genetic linkage.

6.2.2.2 Environmental Radiations

In principle, the RUE will increase as the leaf area with a decrease in saturated light is decreased (Sinclair and Horie 1989). The proportion is determined by variables, including irradiance, diffuse proportion to total solar radiation, and LAI. The elevation in radiation and total radiation is expected since in both situations the share of non-saturated irradiation photosynthesis is increased. Radiation use efficiency is expected to decrease. The effect was shown using simulated variants (Allen Jr et al. 1974; Choudhury 2000), and a minor impact of artificially adjusting the radiation environment in sunflower was reported (Bange et al. 1997). In maize, the estimated net canopy photosynthetic efficiency was 25% in overcast measurements compared with clear-sky conditions in PARs up to 1000 μmolm^{-2} s^{-1} (Micromole per meter square per second) (Rochette et al. 1996). Loomis and Connor (1992) summarized the response to plant’s photosynthetic rate in different species that shows RUE declining gradually as S_t increases, whereby some C_3 species have fallen sharply for S_t greater than 400 Wm^{-2}(Watt per meter square). The size and structure of canopy and RUE may also influence the radiation environment, as discussed above. Irradiance and total radiations are related to temperature and vapor pressure variations under natural conditions. Higher total radiations and lower S_t values, low thermal amplification as a result of moderate cooling during the night or slight heating at dawn, and lower vapor pressure deficit (VPD) are correlated with overcast conditions. Likewise, low total radiations and, in many cases, high VPD are associated with increased irradiance. In eastern Australia, Rodriguez and Sadras (2007) analyzed RUE and argued that total radiations and irradiance describe the latitudinal variance of RUE and the inversion of the relationship that occurs with RUE and VPD, as a result of VPD’s association with these variables. Although explaining for East Australia and other locations is possible, research relies on the hypothesis of its simulation model, which measures radiation-based photosynthesis rate and thereby essentially distinguishes the process of photosynthesis from any apparent stomata regulation. The argument here, however, seems to be that simulation-based separation helps to assess the overall effect on RUE factors which in natural conditions are very difficult to isolate (Hammer and Wright 1994).

6.2.2.3 Relative Humidity

The plant's stomata seem to be close to increase the vapor pressure (Dai et al. 1992) as a result of increased sweating (Mott and Parkhust 1991) and provide clear RUE response system for relative humidity, which might be independent of the photosynthesis impact of radiation levels and total radiations. Stomatal closures, for instance, at noon, often indicate a certain degree of water stress; therefore, reduction in RUE is only observed as a result of the drought or water stress (Kumar et al. 2016; Meena et al. 2017a). The leaves do not possess any sensor which can sense the humidity present in the atmosphere, and may be monitored for the physico-chemical actions. In plants, the leaf stomata respond to vast majority of regulations maintaining good plant water equilibrium and carbon absorption. The influence of air humidity on the field alone, therefore, is difficult to isolate. Nonetheless, the RUE association was found to be negative with VPDs (Stockle and Kiniry 1990). Kemanian et al. (2004) demonstrated that the S_t, temperature, or total radiations of RUE do not eliminate the observed RUE-VPD relationship.

6.2.2.4 Temperature

The temperature regulates the rate of production and the time required for radiation absorption (Murchie et al. 2009). Photosynthesis at leaf level has a significant temperature response. Under normal conditions, leaves will encounter a range of temperature conditions within a single day, from under-optimum to super-optimal level. The daily temperature trend is consistent with one-to two-hour change, as the daily variability of VPD is also correlated. The weather variations will mark the difference between successive days or weeks. Leaves are linked to the energy balance of the atmospheric evaporative demand so that leaves (especially sunlight leaves) maybe some degree Celsius beneath ambient temperature due to cooling generated by transpiration or a degree below surrounding air when transpiration process is restricted. The positive response of RUE to temperatures of 16–21 °C has been recorded by Andrade et al. (1993). Brown et al. (2006) have recorded an alfalfa temperature response of 6–18 °C, a slope lower than maize. Typical temperatures for spring-grown crops of wheat and barley appear to have a small impact on RUE. The temperature variability found in seasonal RUE was not related to the climate, with minimal temperature variations range between 9 and 12 °C and a maximum of 23–28 °C (Kemanian et al. 2004). Awal and Ikeda's (2003) reports on peanuts demonstrated the importance of the factors that affect RUE. The RUE responded positively to the soil temperature ranged between 21 and 26 °C and RUE equals to 0 when the temperature reaches 10 °C. The primary reason is not clear and might include associations with either root–shoot relationships or the nutrient status of the plant. Low temperatures due to photo-inhibition may impair photosynthesis. In the early spring, air and soil surface temperature may be lower during clear days, and high irradiance may trigger photo-inhibition (Long et al. 1983). If photo-inhibition is caused by the combination of both radiations and temperature, RUE must be less than the expected values.

6.2.2.5 Water Use Efficiency

Water stress reduces the photosynthesis process in the leaves and thereby, reduces RUE in several crops, such as, sweet corn (Stone et al. 2001), peanut (Collino et al. 2001), maize (Earl and Davis 2003), and barley (Jamieson et al. 1995), which exhibited lower RUE under water stress. Water scarcity decreased the RUE, influences the canopies growth but also radiations (Jamieson et al. 1995). The status of water requirement in crops is determined by the equilibrium between demand for water requirement and the availability of transpiration rate. Water stress can also be minimized through both stomatal and non-stomatal responses to minimize leaf photosynthesis rate (and RUE). The water stress may result in the closing of stomata, which reduces the availability of CO_2 inside the leaves, may stimulate photo-inhibition, which may come under non-stomatal effects due to lower leaf water potential, will impede photosynthesis and might reduce photosynthetic rate due to an over-heat leading to decreased cooling mediated by transpiration (Valladares and Pearcy 1997). Stressed to non-stressed everyday wheat RUE ratio is a function of the simulated reality to theoretical transpiration and demonstrating that RUE decline because of water deficiency is not, as is often thought, linearly associated with a reduction in actual to possible transpiration. The explanation is that photosynthesis decrease is slighter than evaporation in the initial stages of water stress. While the stomata closure almost proportionally reduces transpiration (thermal effect), the internal CO_2 concentration in leaf also declines due to plants photosynthesis, leading to a higher leaf-to-air CO_2 ratio than during no water deficient condition.

6.2.2.6 Source-Sink Relationship

Photosynthesis can be down-regulated by the deposition of surplus photosynthetic products in the leaves (Paul and Peliny 2003). It is, therefore, possible to use the RUE to deplete photosynthetic products on the ability to grow organs and transport systems. The photosynthesis can be controlled or stimulated through a large number of kernels (or by single leaf mass or per unit leaf N) during grain filling stage (Geiger 1976). The definition is indeed true for every kind of developing organs, such as stalks and roots. The RUE tends to be correlated with the source-sink relation throughout the grain filling stage, while RUE eases in the sunflower and wheat (Miralles and Slafer; 1997 Sadras et al. 1991). In this regard, wider experimental proof is greatly required. The grain filling allows a comparatively easy analysis system to monitor source-sink ratio since the source-to-sink ratio is easy to change by artificially altering the amount of growing grain. Alternative ways to adjust such balance are to minimize disruption throughout the canopy or root environment through an increase in radiation dose per unit leaf area. Alterations, which permit manipulations at a large-scale, the removal of such complete rays to enhance the dispersion of light, may also have an impact on the environment of the root and the energy balance. One of the most undiscovered and fascinating aspects of the control of photosynthesis at canopy level is the restricted use of photosynthetic RUE through the source-sink balance. It may be the source of the observed growth differences in perennial grass and annual grasses growth in temperate regions at beginning of the fall; where growth rates are significantly greater than those of *Phalaris*, orchard, and perennial bromegrass, or grains crops in the annual grasses like oats or barley, or the variations found in photosynthetic radiations-use efficiency, being utilized by expenses of cereal grains (C_3) and other legumes for biosynthesis.

6.2.2.7 Crop Nutritional Status

As nutrition influences the rate of photosynthesis under nutritional stress, RUE will decrease. Based on hypothetical underpinnings from RUE, it has been observed that a decline in RUE was recorded as N deficiency rises with a decrease in leaf photosynthesis rate, both the processes were closely associated (Sinclair, and Horie 1989). Theoretically, low RUE was widely documented in N-stressed crops (Gallagher and Biscoe 1978; Fischer 1993). Nevertheless, no single RUE response should be entitled to nutritional status. The maximum photosynthesis rate is less important for the determination of net photosynthesis in lowlight intensity. As the LAI increases, shaded leaves can use more radiation through the sunlight leaf area, which in turn operates at an unsaturated light intensity. The distribution of N in canopy also helps to permit efficient utilization of sunlight for net photosynthesis. The upper portion of the leaf, which more sun-lit is present than those in shaded leaves, has generally higher leaf N (and are younger). Therefore, average leaf N for the leaf does not accurately represent the leaf N required to measure RUE accurately. Employing an elegant simulation study, Hammer and Wright (1994) reported that N accumulation in canopy influences RUE, when the mean leaf N is small. Deficiency of phosphorus may also affect crop efficiency (Mitran et al. 2018). Rodriguez et al. (2000) have observed that the phosphorus deficiency of the plant's leaf region of wheat had decreased leaf expansion and leaf growth assimilates, which led to a reduction of 63% and 46% in $f_{i,}$ and 21% and 31% in radiations absorption, after 61 days of seedling emergence in the shaded and non-shaded crop species, respectively. Nevertheless, Plenet et al. (2000) reported no impact on RUE corn deficiency, even when the biomass accumulation in the shoot was the most significantly decreased, with a decrease in bulk induced by a reduction in LAI (reduced radiation capture) rather than decreased photosynthesis by leaf area.

6.2.2.8 Partitioning Between Root and Shoot Biomass

The majority of RUE inferences are focused on shoots biomass accumulation. More RUE estimates the utilization of the micro-meteorological approaches for net CO_2 accumulation in canopy distribution like root extension and their exudates (Brown et al. 2006). All strategies need some preliminary precautions. The micrometeorological approaches require respiration of soil micro-biota estimates to measure the stability between crops and carbon (Meena et al. 2020a). While the plant roots ignores the exudates released from the root zone and plant turnover, which may constitute a considerable proportion of the energy efficiency for crop carbon (Amos and Walters 2006). The trend in plant carbon allocation in alfalfa with upward and downwards alterations in the field is substantially seasonal, and RUEs determination based on spring biomass is quite misleading (Brown et al. 2006; Kumar et al. 2018; Meena et al. 2019). Root and shoot partitioning may moderately describe the comparatively low RUE during early growth stages in annual plants simply if the shoot biomass is sampled. Trapani et al. (1992) reported that roots of sunflower were overlooked and RUE was underestimated at approximately 20% during the early development phase (LAI < 1.7), while in the linear growth phase, it was 4%. Radiation use efficiency detection has been obtained significantly less consideration during early growth even after canopy closure. The explanation behind this is that radiation sensor bars can be difficult to install underneath small plants, but remote sensing-based inversions may provide the precise f_i approximates. The other reason behind this is that the parameter estimation is of little effect because RUE is measured based on radiation interception and accumulated biomass with the minimum error in square fitting, early radiation intercept, and weak biomass. The RUE should be defined as far as possible for time frames that differ slightly, that maybe quite difficult to accomplish during the early phases of canopy development. Radiation use efficiency study is specifically a field in which research needs to be done for early canopy development.

6.3 Nitrogen Use Efficiency and Its Influence on Crop Physiology

Nitrogen availability to soil has been a major constraint for crop productivity (Meena et al. 2016a). The utilization of N in different crops and cropping systems can be achieved by the use of legume cropping and N fertilizers, represents as one of the major components to produce enough food supply to fulfill the increasing demand of the growing population (Eickhout et al. 2006; Kakraliya et al. 2018b). During past 40 years, global consumption of N fertilizer has enhanced seven times as agricultural food production doubles. Moreover, N exploitation has contributed to the significant environmental factors, like aquatic environments (Beman et al. 2005), and offshore eutrophication (London 2005), and gaseous nitrous oxide (N_2O) and releases of ammonia (NH_3) into the soil by a series of N cascade events (Galloway and Cowling 2002). A relatively high price ratio between grain and fertilizer, particularly in the subsidized farming system, prompted farmers for many years to use excess N to achieve high yield and gain. This approach can effectively increase the N content in soil composition (Addiscott et al. 1991). Together with extensive duration of N residence in the soil organic material, this effect shows that soil contamination present in water, which was observed, may be a consequence of the delay in the crop intensification systems a two decades ago (Mariotti 1997). The efficacy of the application of N fertilizer in farm systems is also questioned by the challenges correlated with biofuel production, climate change, and sustainable food security (Cassman 2007).

Nitrogen use efficiency has to be described by a very general term. It is mainly an agricultural term to begin with. It has two basic meanings, both of which are used when the word is being used simultaneously. The primary concept of NUE is the productivity of crops utilizing and maintaining N in the soil. The explanation for this NUE interpretation is that the plant prefers to release the N into the atmosphere in the form of N_2O, rather than retaining it in its body (Daigger et al. 1976). Legumes attain higher NUE since they absorb and accumulate N inside their cells instead of releasing it into the environment (Vinod et al. 2016).

Nevertheless, is it still a question of debate, either the net N loss is much smaller for legume crops other than for other species, as a little loss may occur when leguminous and other crops are decomposed (Volpe et al. 2016; Rani et al. 2019). The NUE estimates the total concentration of N utilized in the plant, along with the concentration of N assimilated in plants. It tests how much plants use and maintain N efficiently. All plant's N collections are classified as soil N, and all emissions of N_2O are believed to occur in the soil before plant's N absorption for the production of N_2O as plants can consume ammonium ions and nitrate (NO_3) ions via their roots (Choi et al. 2009). This NUE estimation approach leads to the first concept of the efficiency of N usage.

Secondly, NUE is defined as the efficiency, in which plants may use a natural or artificial form of using N added to soils and not being utilized for any further purpose, including supplying anaerobes, which may induce denitrification and leaching by N absorption in the water (Koffi et al. 2016). The excessive soil runoff (due to lack of organic matter in the soil), over-dosage of fertilizers, or slugged growth are frequent factors in N dissolution within water (Daniel et al. 2010). The excess water in fields induced the anaerobic denitrification (Matejek et al. 2010). The NUE in cultivating soil measures how much N was fixed at the beginning of the season, how much N is lost by leaching and denitrification as well as how much N has been left in the soil through a soil sample analysis, and in soil analysis. Higher is the amount of N used up by the crop, and more effective the plant is to use N, relative to the amount left or lost in the soil. In consideration of fertilizer use, this is particularly relevant as the optimal condition is that no more fertilizer can be misused and consumed for the benefit of crops on which the fertilizer can be employed (Peltonen et al. 1995).

Ultimately, NUE is the precise utilization of N in the soil. The efficiency of N usage describes how much N is used in a crop and maintains until harvest relative to the quantity of N currently accessible for the crop with special emphasis on how much amount of fertilizer is used in the soil as opposed to how much amount of N is used in the plant and retains it until the harvest (Raun and Johnson 1999). It has been commonly used as in metric terms to equate N absorption to total of N. The mass of the seeds harvested as compared with N mass used; is one of the ways about explaining NUE. Due to the variations in the crop yield productivity, loss of N in the field and corn and N fertilizers price volatility, fertilization practices are essential to optimize the exploitation of N fertilizers.

The NUE is a complex feature. The productivity of N usage in conventional agricultural practices all over the world is regarded as very small on average (Raun and Johnson 1999), even in the developing world. The utilization of nitrogen fertilizers has dramatically augmented worldwide, increasing just from 79 to around 99 million pounds in 2002 and 2012, respectively. In contrast, worldwide crop yields in comparison to the N fertilizers used in the plants have hardly increased. It indicates that N fertilizer use is extremely inefficient. The NUE for global cereal production is quite low, and the average N recovered by the crop is estimated at 33%. The primary reason for N loss is leaching of NO_3 ions in the soil or denitrification due to the excessive precipitation. In Missouri, the farmers applied the N before sowing or planting and said that N application is highly vulnerable to N spring loss in the fall, leading to crop yellowing. During the time between application of N and its successful retention in the soil, N losses from leaching, the soil fixation, immobilization, denitrification, and the volatilization provide several opportunities (Scharf and Lory 2002). The minor synchronization between N application and the crop requirement is partly the cause of lower NUE of the existing N practices for management (Cassman et al. 2002; Abebe and Feyisa 2017). Another contributing factor to lower NUE is standardized N applications levels of landscape areas that differ in size and in time, although numerous reports have shown environmental and economic reasons for spatially complex applications of N (Mamo et al. 2003). Several strategies were adopted to calculate the actual N requirement of each crop, but the efficiency of N is poor because of uncertainties in its methods of calculation.

Based on these environmental and socioeconomic aspects, the N performance of cultivation systems needs to be improved. The NUE depends on agricultural practices such as organic and legume fertilizers, minerals, and genetic advancement of N use. It is difficult to follow a more restricted approach for the availability and duration of N fertilizers applied to the crops due to confined estimation of soil mineralization and the ability to grow crops. For different agricultural regions, precipitation incertitude is a crucial aspect for fertilizer application decision-making, whether because of inadequate rainfall that limits crop production and mineralization of soil nor it is because surplus precipitation raises the possibility of leaching of NO_3 ions (Sadras 2002; de Koeijer et al. 2003; Sadras and Roget 2004; Cabrera and Jagtap 2007). Nitrogen application significantly decreases to prevent soils against excess N, which may raise the risk of N deficiency in crops for a short duration, e.g., if the supply of soil N does not fulfill the demand of the plant N. Rather, molecular and conventional breeding strategies would improve the crop's N efficiency in both circumstances of chronic and other pedoclimatic restrictions, which are favorable to over usage of N fertilization (subsidized industry, high intrinsic productivity, the high price of grain to N). To optimize crop growth and production with the least contribution to minimize several environmental risks, it is important to understand the mechanism and features that may govern N absorption, its distribution, and crop productivity responses (Cassman et al. 2002).

6.3.1 Leaf Nitrogen and Photosynthetic Rate Relationship

Several studies have examined the relationship between the content of leaf N and the rate of assimilation of leaf CO_2, particularly in soybean and rice. Since the photosynthetic apparatus associates a considerable fraction of leaf N, it is no surprise that there has been a high correlation. The leaves of C_3 plants alone make up 50% of the total soluble protein for Rubisco (ribulose 1,5-bisphosphate carboxylase), while the C_4 contains 10–25% (Schmitt and Edwards 1981) of the soluble protein. Brown (1978) also reported that phosphoenolpyruvate carboxylase is another 10% soluble protein in C_4 leaves. Consequently, leaf content N per area unit (N_{ag} Nm^{-2}) may represent the carbon assimilation of leaf potential per unit area (mg CO_2 m^{-2} s^{-1}) in several cases (Kumar et al. 2020).

6.3.2 Correlation Between Deposition of Leaf Nitrogen and Plant Biomass

Although scientific evidence found a link among increased availability of N for crop production and enhanced deposition of crop biomass, quantitative methods for the analysis of N accumulation are difficult to achieve. Preliminary functions that define the response of accumulation of crop biomass to quantity and utilization of N in the initial stages of crop growth can be developed using previous derivatives. Such interaction will be exploited in a simple way of examination to explore the trade-offs between the N and the leaf area in early cultivation production.

6.3.3 Nitrogen and Crop Biomass Accumulation

Several factors affect crop biomass, including, soil moisture, air temperature, solar radiations, duration of photoperiod, precipitation, genotypes, etc. Soil nutrient availability is one of the most important factors that influence biomass. Thus, it is possible to maximize the optimum availability of nutrients in the soil, the production of biomass and, obviously, economic advantages (biomass production), for farmers. Use of fertilizers is perhaps the most common practice among farmers to increase the low nutrient status in areas, where there is insufficient nutrient supply (Sharma et al. 2019). Nitrogen deficiency contributes to many crops to a significant decrease in plant photosynthesis, with more than half of the total N leaf allocated to the photosystem (Makino and Osmond 1991). There is clear proof that N deficiency causes a decrease in growth in the whole plant (Paul and Foyer 2001). Nitrogen deficiency leads to carbohydrate accumulation in the leaves, high concentration of carbon allocation to the roots, and decreased ratio of plant to shoot biomass (Hirai et al. 2004). The N deficiencies, therefore, influence the photosynthesis process, sugar mobilization, and carbohydrate assimilation between sources and sink tissue (De Groot et al. 2003; Hirai et al. 2004).

The usual patterns of N accumulation in dry biomass are important for establishing an adequate plant nutrition level. The quantity and proportion of the nutrients accumulated depend on plant features and environmental factors. The nutrients obtained from soil and plants differ according to variety, plant growth cycle, land practices, and other accessible plant growth parameters (Benett et al. 2013). The most important nutrient is N and it is crucial for rapid growth at early stage, quality, as well as yield of crops. Significance of N in plants is linked with plants encompassing grass category with the maximum photosynthetic potential, namely, the metabolism of C_4, with a high rate of photosynthesis, effective N and solar energy use, and high dry biomass production efficiency, is a particular feature of the high efficiency in dry biomass production (Franco et al. 2010). Nitrogen fertilizers enable a substantial increase in aerial dry biomass (Otto et al. 2009). N fertilizers also enhanced the dry biomass accumulation upon its application (Almeida Júnior et al. 2011). Thus, it is imperative for improving plant growth, considering its genetic potential, to use irrigation technologies and N fertilization (Farias et al. 2008). In addition to being essential for growing and developing multiple cultures (Lawlor and Cornic 2002), the availability of water on soil affects the fertilization quality, solubility, and subsequent nutrient releases to the plant. The optimal water conditions and sufficient N supply can, therefore, help root production (Robinson et al. 1983). The lack of N results in the highest growth limitation in contrast to other macronutrients, since the structural functions of N are involved in different organic substances and other basic physiological and biochemical mechanisms (Prado et al. 2010). The information regarding concentration of mineral nutrients assimilated in plants offers knowledge which may help with the management of fertilizers. It also leads to improving crop productivity by increasing the production of total biomass, enhancing the transition of assimilates to crops harvested and promoting the successful use of fertilizers (Carmo et al. 2011).

6.3.4 Nitrogen Remobilization and Plant Senescence

In plants, the process of senescence is the final phase of the developmental stage before the plant dies (Lim et al. 2007). During senescence, macromolecular destruction and elimination of nutrients help the plants to recover the nutrients inside the cells (endogenous) (Himelblau and Amasino 2001; Gregersen et al. 2008). The process of senescence is mainly a mechanism, which is mainly based on age, regulated using both external and internal recurrent signals, and typically transformed by hormones (Jibran et al. 2013). Several external constraints, including the excessive temperatures, low/high radiations, lack of water and nutrients, and pathogenic infections can cause precocious senescence, which allows the crop to accumulate nutrients in other plant sections for growth and restrict the invader during the situation of a biological attack (Lim et al. 2007; Rapp et al. 2015). The leaf senescence typically correlates with reproductive development for the annual cereal food crops, for example, winter wheat, soy, maize, and rice perhaps as a response to resource requirement signals in developing sink tissue (Noodén and Penney 2001;

Kakraliya et al. 2017a, 2017b). The remobilized nutrients are primarily used for seed (grain) growth by blooming leaves and stalks, providing optimum reproductive attainment. Higher N in flag leaves remobilize the proteins and micronutrients in rice and wheat grains (Liang et al. 2014; Uauy et al. 2006). The quality and yield potential of cereal grains seem to be strongly associated with the efficiency of nutrient restoration in plant metabolism, although, the grain yield and protein content, in general, are negatively correlated (Bogard et al. 2010). Small cereals such as rice, wheat, and barley could mobilize up to 90% N in vegetative tissues to the seed; however, this differed from the genotype to the species (Kichey et al. 2007; Kumar et al. 2017a, b; Kakraliya et al. 2018a). N-remobilization from different plant organs significantly contributed in pea around 71% of total amount of N in the harvested grains (Schiltz et al. 2005). Nevertheless, significant fraction of the vital minerals and nutrients persists after senescence in the different tissues. For instance, under field conditions, approximately 7.0 kg nitrogen, 9.7 kg potassium, and 1.1 kg phosphorus still stay under field conditions in every ton of maize stove (Johnson et al. 2010). But this is eliminated from ground, it should be introduced to sustain soil fertility by matching fertilizer levels.

In comparison to many dicots, most of the perennial herbs, including dedicated biomass plants including miscanthus, switchgrass, and the giant reeds, avoid vegetative development after breeding (Moore et al. 1991). Senescence takes place each year on every organ above ground (leaves, stalks, and spikes), under natural soil conditions, after anthesis and pollinating. A part of the nutrients that have been remobilized from the leaves and stumps is distributed to soil systems (root, rhizome, and crowns) in addition to supporting for seed production (Lemus et al. 2008; Nassi o Di Nasso et al. 2011, 2013; Dohleman et al. 2012; Kering et al. 2012), in which it act as the next season's nutritional reserves. For sustainable production of biofuels from appropriate biomass, nutrient regeneration to underground species is critical (Meena et al. 2018a). Several switchgrass accessions have shown that around 61% of N can be removed in tillers at harvesting stage (Yang et al. 2009). In harvested shoot biomass, nevertheless, significant amounts of soil nutrients tend to be lost in shoot biomass at physiological maturity (Propheter and Staggenborg 2010; Guretzky et al. 2011). For example, in autumn single-shoot harvesting system, total N extracted from biomass of switchgrass ranged from 31 to 63 kg N ha^{1} year^{-1} and in two-shooting system ranged from 90 to 144 kgNha^{-1} year^{-1} over five seasons of measurement (Reynolds et al. 2000). Considering that biomass enriched in N content is not advantageous to bioenergy production, yet requires additional N fertilizer to maintain the productivity of switchgrass in the next growing season, the N content of bioenergy production should be further lowered, for example, by that N-remobilization at shoot senescence. Contrary to biofuel biomass, it is best to use biomass obtained from perennial grasses used for livestock's drilling when the animal contains high protein-N. Delays in senescence (and delays in the remobilization of N) would be therefore desirable, particularly if it allows for continuous photosynthesis and growth until then, to retain more protein in their feed before consumption.

6.3.5 Nitrogen Crop Modeling

Nitrogen emissions are an important environmental concern. Nitrous oxide as a greenhouse gas has a greater potential to warm the atmosphere than CO_2.The major source of N_2O production in agriculture is estimated to be N fertilizers. Accurate assessments of N movement through agricultural systems are a critical need. However, the production of N_2O in agricultural systems is complex (Fig. 6.4), whose reduction is still challenging.

Nitrogen utilization efficiency is often poor in production agriculture, leading to loss of the excessive amount of N to groundwater such as $NO^-{}_3$, NH_3, and N_2O gaseous emissions, and N depletion of surface water runoff and soil erosion. The best management practices (BMPs) are necessary for enhancing the production effectiveness and at the same time as preserving the crop nutritional requirements. All time consuming and expensive field studies aimed to examine possible BMPs cannot address all scenarios. Simulation models are progressively used in crop productivity and environmental impact assessment, which can be derived from given temperature, soil, crop properties, and combinations of water and N management combinations (Stockle and Debaeke 1977). In combination with the associated field studies, the implementation of N-cycling component simulation models provides a technique that might help to identify BMPs, which are promising for increasing the amount of NUE but with reduced costs and time. For this reason, it is necessary to adequately simulate crop N specifications both in volume and in

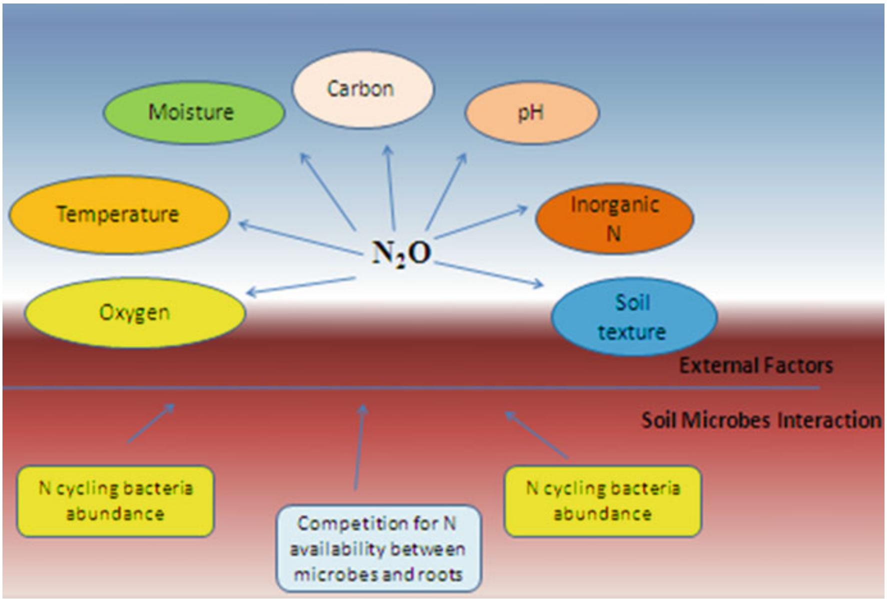


Fig. 6.4 The dynamism of nitrous oxide production

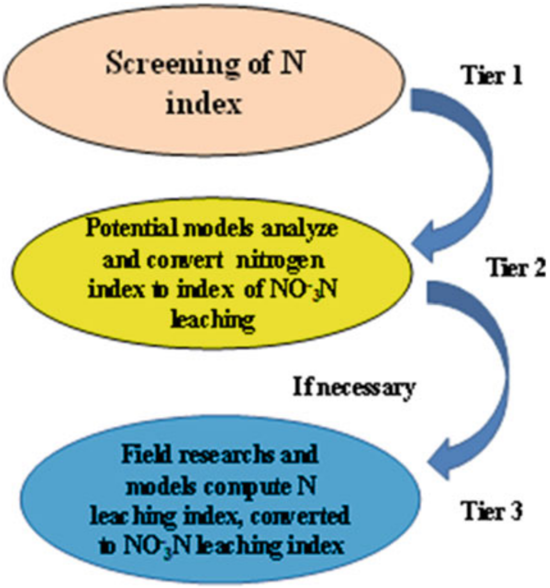


Fig. 6.5 7 3-tier model of NO_3^--N leaching index (Shaffer and Delgado 2002)

distribution during the growing season. Many techniques to the simulation of crop N specifications have been suggested.

Cases that successfully use modeling to classify possible BMPs for increasing NUE and the reduction of NO_3-N leaching, provide examples from rainfed agriculture, geographical information systems (GIS), irrigation, remote sensing, and site-specific farming examples are provided, and precision conservation is provided. Nonetheless, reliable BMP studies utilizing simulation technology will take a clear route involving the selection adjustment, and calibration of models, analysis of sensitivity, data needs, and availability, implementation of models and model interpretation, as well as restrictions. The models can then be applied to evaluate different global placement systems (GPS), GIS, and remote sensing-based BMPs, which can then evaluate the efficient and cost-effective use of N at low cost and time. Researchers are continuously developing and improving NUE-enhancing BMPs. Given the complexity of the environment, plant systems, weather, field and farm studies covering every possible scenario, and management scenarios, cannot be undertaken. The computer simulation and decision support models are viable alternatives in N-cycle soil culture systems that can assist in testing different combinations of management strategies and their effects on N recovery under certain conditions by the farming system. This is especially true when combined with economics and GIS. Such designs exhibited the complex databases and algorithms, which may deal under diverse circumstances and may act as mechanical routes to test several NUE and system's sustainability scenarios and impacts. Shaffer and Delgado (2002) suggested a three-tier method to access N management tools and practices (Fig. 6.5).

Implementing the field test models under complex conditions and a wide range of possible management scenarios will challenge agricultural directors and those needing accurate, timely, and objective responses. Model users can easily handle various issues such as model selection and database creation, input data collection in the domain, model analysis setup, model management scenarios design, model installation and functionality, model configuration, and local testing, results, and interpretation. All these model elements need to be managed effectively and efficiently to achieve good modeling performance.

Numerous model farming systems having the capability to enhance C and N cycles are available worldwide. The selection of a model for a certain area and application is not a trivial task and includes an understanding of the model ability, limitations and problem, and position. Several environmental and management issues have been addressed by C/N (Carbon/Nitrogen) models like NO_3^- leaching, carbon sequestration, pollution from greenhouse gases, and the management of soil fertility. Detailed explanations of the normal C/N model implementations are described by Shaffer et al. (2001). The specificities of these models are somewhat different and involve extremely detailed testing models and user-based screening instruments. The US Models (Ma and Shaffer 2001); the European Models (McGechan et al. 2001); and Canadian Model Ecosys (Grant 2001) provide detailed evaluations and comparisons of such models. The potential user will analyze, test models, check the project specifications, and pick the design suitable for the product. Generally, somewhere in the middle, the best model for a specific application is maximal usability.

The choice of a model which is either too basic or too complicated for a specific application or which is impractical has raised many software design research problems and should be avoided. For a suitable project, potential users must understand the applicability, data needs, ease of use, databases on the needs supplied, and model capabilities. For example, if a particular cropping method involves a project, but a model is unable to deal with that situation, then that specific model is not used. However, if certain models do not include databases on land and the environment, more research will also be needed to build certain instruments, which might be necessary to choose the final model. If in an area with substantially varying requirements, then the proposed project, a model was designed and tested, the additional effort would probably be required to modify and adjust the model for the local region. Software models for the C/N dynamics simulation include root zone water quality model (Ahuja et al. 2000); the Canadian model, ecosys (Grant 1997); erosion/productivity impact calculator (Williams et al. 1983); great plains framework for agricultural resource management (Ascough II et al. 1998); crop estimation through resource and environmental synthesis (Ritchie et al. 1985); CANDY (Franko 1996); NTRM (Shaffer and Larson 1987); SUNDIAL (Bradbury et al. 1993); LEACHM (Wagenet and Hutson 1989); the Swedish model, SOILN (Eckersten et al. 1998); NLEAP (NO_3 leaching and economic analysis package, Shaffer et al. 1991); CENTURY carbon model; the Rothamsted N turnover model, the German UFZ model, ICBM (Andren and Katterer 1997); and German design, HERMES (Kersebaum 1989). A number of these models possess websites containing product specifications and, in some cases, newest models and designs and their associated databases. An internet search engine like the "GOOGLE" must be utilized to find the actual website addresses for these apps.

6.4 Current and Future Challenges

Nitrogen is important for plant growth; therefore, N fertilization helps farmers to produce high yields and enough agricultural commodities, while the depletion of N will lead to the adverse environmental and human health consequences. Increased efficiency in N usage is crucial if the conflict between productivity and the protection of the environment is to be solved, secure a growing world population's demand. Ensuring genetic enhancement is seen as a key aspect of environmentally friendly crop cultivation (Stahl et al. 2017).

To understand the NUE control and its effective utilization by the plants, it would be essential to provide the tragets for the breeders and monitoring tools for farmers in carrying out a ration some fertilization protocol, a strategy incorporating genomic, physiological, and agronomic analysis of the whole plant N response will be required for its implementation. This hypothesis outlines the main points for developing a successful gene-discovery research program by systematic and comprehensive phenotypes of crops grown under low and high N fertilization applications like agronomical, biochemical, and physiologic studies on crops (Hirel et al. 2007).

Each strategy may use alone, but a combination solution may help to improve NUE. The use of optical sensors in long-term prospects may only contribute to increased NUE and farmers' benefits if exact data is collected from several places, which take into account differences in land, the environmental and cultural practices, and a robust return prediction model. The solution for improved N production could be to use sensor-based periodic nutrient management in conjunction with early soils testing and splitting applications (Sharma and Bali 2017).

We expect that RUE should continue to be increasingly important in determining crop production and lead to increased productivity in performing field experiments. The RUE calculations can help to determine whether the crop uses intercepted radiation at its maximum output and also the several other factors which may hinder the crop production. A comprehensive data collection for RUE evaluations is a powerful tool to understand crop growth and yield (Sinclair and Muchow 1999a, b)

Natural resource productivity has been fundamental to farming practice for more than 10,000 years. Because humans are being engaged in several natural ecosystems to obtain the food, a conflict has been raised in enhancing the agro-ecosystem performance. If performance is essentially the amount of output per input unit, "eco-efficiency" as opposed to ecological resources, mainly nutrients, soil, water, energy, or biodiversity, aim at this simple concept of the production of food and fiber (Keating et al. 2010).

Evaluation of plant production for climate change food and energy is difficult without updating the model with LAI and RUE feeds and the right decisions to change environmentally friendly crop rotations. This is motivated by a greater understanding of LAI production, the plant phenology, and the role of RUE and LAI in regulating the productivity of various crops such as rapidly growing trees and plant tolerances for climate change (Tripathi et al. 2018).

6.5 Conclusions

This chapter intended to focus on crop radiation and nitrogen use efficiency (NUE) in plants and their management practices. Radiation use efficiency (RUE) and separation of radiation provide a safe and resilient environment for crop growth analysis as well as treatment comparisons. The chief physiological variations of C_3, $C_{4,}$ and legume crops are reported for various species under maximum RUE. Capturing radiation and the RUE can also provide a simple way to simulate agriculture by modeling accrual radiation biomass and the RUE if ecological and other environmental conditions have to be taken into consideration. To attain agricultural and crop breeding purposes, this method offers a prevailing means for comparing the managements on the same site for farming or breeding purposes; comparisons between sites are more careful and still workable. The field implementation of the N management patterns questions the selection of the suitable model from lengthy record of possible resources and afterwards application of the system to field conditions which are often excluded from the development and implementation of the model. The N fertilizer is a two-edged sword for farming that is vital to high food, feed, fibers, and fuel returns (per unit area and time), however, it harms human health and the environment in the current application. Increasing NUE will help strengthen one face of the N-word and reduce the impact on the environment. This is a great outlook that is to be tested in the coming years.

6.6 Future Perspectives

The application of RUE AND NUE with existing technologies for the improvement of soil-crop management practices must be explored step by step. New mechanized tools with good reliability, cost-effective, and easy to handle should be utilized to gather information regarding plants nutritional status with respect to solar radiations and fertilizers usage. Intercropping system that may have positive liner function with yield and PAR should be further explored for crop productivity (Layek et al. 2018). The correlation between photosynthesis and biomass accumulation at either stage of crop development requires further investigations either it is invested for growth or storage? Also, the most diverse resource available for plants is the light intensity. Being sedentary, plants are exposed to very high or low extremes of irradiance over day time. A precise model revealing the canopy photosynthesis and its related physiological responses must be elucidated to determine the net influx of solar radiations. Timing and severity of senescence by traditional breeding and genetic engineering can be optimized so that crop species may utilize N and photosynthetic radiations more efficiently. This is an exciting possibility, which will be tested in the coming years. Future research includes a multi-disciplinary approach involving not only agronomists, soil scientists, and farmers but also ecologists, policy-makers, and social scientists.

References

Abebe Z, Feyisa H (2017) Effects of nitrogen rates and time of application on yield of maize: rainfall variability influenced time of N application. Int J Agron 2017:1–10

Addiscott TM, Withmore AP, Powlson DS (1991) Farming, fertilizers, and the nitrate problem. CAB International, Wallingford

Ahuja LR, Rojas KW, Hanson JD, Shaffer MJ, Ma L (2000) Root zone water quality model. Water Resource Publication, Highlands Ranch

Akmal M, Janssens MJJ (2004) Productivity and light use efficiency of perennial ryegrass with contrasting water and nitrogen supplies. Field Crops Res 88:143–155

Allen LH Jr, Stewart DW, Lemon ER (1974) Photosynthesis in plant canopies: effect of light response curves and radiation source geometry. Photosynthetica 8:184–207

Almeida Júnior AB, Nascimento MFS, Silva FBV, Gomes WA (2011) Soil fertility and uptake of nutrients by sugarcane fertilized with filter cake. Rev Bras Eng Agríc Ambient 15 (10):1004–1013

Amos B, Walters DT (2006) Maize root biomass and net rhizodeposited carbon: an analysis of the literature. Soil Sci Soc Am J 70:1489–1503

Andrade FH, Uhart SA, Cirilo A (1993) Temperature affects radiation use efficiency in maize. Field Crops Res 32:17–25

Andren O, Katterer T (1997) ICBM: the introductory carbon balance model for exploration of soil carbon balances. Ecol Appl 7:1226–1236

Ascough JC II, McMaster GS, Shaffer MJ, Hanson JD, Ahuja LR (1998) Economic and environmental strategic planning for the whole farm and ranch: the GPFRAM decision support system. In: Proc. First Interagency Hydrologic Modelling Conference, Las Vegas

Awal MA, Ikeda T (2003) Effect of elevated soil temperature on radiation-use efficiency in peanut stands. Agric For Meteorol 118:63–74

Bange MP, Hammer GL, Rickert KG (1997) Effect of radiation environment on radiation-use efficiency and growth of sunflower. Crop Sci 37:1208–1214

Beale CV, Long SP (1995) Can perennial C4 grasses attain high efficiencies of radiant energy conversion in cool climates? Plant Cell Environ 18:641–650

Beman JM, Arrigo K, Matson PM (2005) Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. Nature 434:211–214

Benett CGS, Buzetti S, Benett KSS, Texeira Filho MCM, Costa NR, Maeda AS, Andreotti M (2013) Amount of nutrients in stalk of sugar cane as a function of sources and doses of manganese. Rev SeminCiêncAgrár 34(3):1077–1088

Biswas B, Gresshoff PM (2014) The role of symbiotic nitrogen fixation in sustainable production of biofuels. Int J Mol Sci 15:7380–7397

Bogard M, Allard V, Brancourt-Hulmel M, Heumez E, Machet JM, Jeuffroy MH, Gate P, Martre P, Le Gouis J (2010) Deviation from the grain protein concentration–grain yield negative relationship is highly correlated to post-anthesis N uptake in winter wheat. J Exp Bot 61:4303–4312

Bonhomme R (2000) Beware of comparing RUE values calculated from PAR vs solar radiation or absorbed vs intercepted radiation. Field Crops Res 68:247–252

Bradbury NL, Whitmore AP, Hart PBS, Lenkinson DS (1993) Modeling the fate of nitrogen in crop and soil in the years following application of 15N-Iabeled fertilizer to winter wheat. J Agric Sci 121:363–379

Brown RH (1978) A difference in N use efficiency in C_3 and C_4 plants and its implications in adaptation and evolution. Crop Sci 18(1):93–98

Brown HE, Derrick JM, Moot EJ, Teixeira EI (2006) Radiation-use efficiency and biomass partitioning of lucerne (*Medicago sativa*) in a temperate climate. Eur J Agron 25:319–327

Cabrera VE, Jagtap SS, Hildebrand (2007) Strategies to limit (minimize) nitrogen leaching on dairy farms driven by seasonal climate forecasts. Agric Ecosyst Environ 122:479–489

Calderini DF, Dreccer MF, Slafer GA (1995) Genetic improvement in wheat yield and associated traits. A re-examination of previous results and the latest trends. Plant Breed 114:108–112

Campbell GS, van Evert FK (1994) Light interception by plant canopies: efficiency and architecture. In: Monteith JL, Scott RK, Unsworth MH (eds) Resource capture by crops. Nottingham University Press, Loughborough, pp 35–52

Canfield DE, Glazer AN, Falkowski PG (2010) The evolution and future of Earth's nitrogen cycle. Science 330:192–196

Carmo GA, Oliveira FRA, Medeiros JF, Oliveira FA, Campos MS, Freitas DC (2011) Leaf content, accumulation and partitioning of nutrients in pumpkin crop irrigated with saline water. Rev Bras Eng Agríc Ambient 15(5):512–518

Cassman KG (2007) Climate change, biofuels, and global food security. Environ Res Lett 2:11–12

Cassman KG, Dobermann A, Walters DT (2002) Agro-ecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31:132–140

Chien SH, Teixeira LA, Cantarella H, Rehm GW, Grant CA, Gearhart MM (2016) Agronomic effectiveness of granular nitrogen/phosphorus fertilizers containing elemental sulfur with and without ammonium sulfate. A Review Agron J 108:1203

Choi JH, Maruthamuthu S, Lee HG, Ha TH, Bae JH (2009) Nitrate removal by electro-bioremediation technology in Korean soil. J Hazard Mater 168:1208–1216

Choudhury BJ (2000) A sensitivity analysis of the radiation use efficiency for gross photosynthesis and net carbon accumulation by wheat. Agric For Meteorol 101:217–234

Chu G, Wang Z, Zhang H, Yang J, Zhang J (2016) Agronomic and physiological performance of rice under integrative crop management. Agron J 108:117–128

Collino DJ, Dardanelli JL, Sereno R, Racca RW (2001) Physiological responses of argentine peanut varieties to water stress. Light interception, radiation use efficiency and partitioning of assimilates. Field Crops Res 70:177–184

D'Antuono LF, Rossini F (1995) Experimental estimation of linseed (*Linumu sitatissimum* L.) crop parameters. Ind Crop Prod 3:261–271

Dai Z, Edwards GE, Ku MSB (1992) Control of photosynthesis and stomatal conductance in *Ricinus communis* L. (castor bean) by leaf to air vapour pressure deficit. Plant Physiol 99:1426–1434

Daigger LA, Sander DH, Peterson GA (1976) Nitrogen content of winter wheat during growth and maturation. Agron J 68:815–818

Daniel FB, Griffith MB, Troyer ME (2010) Influences of spatial scale and soil permeability on relationships between land cover and baseflow stream nutrient concentrations. Environ Manag 45:336–350

De Groot CC, Marcelis LF, van den Boogaard R, Kaiser WM, Lambers H (2003) Interaction of nitrogen and phosphorus nutrition in determining growth. Plant Soil 248(1–2):257–268

de Koeijer TJ, de Buck AJ, Wossink GAA, Oenna J, Renkema JA, Struik PC (2003) Annual variation in weather: its implications for sustainability in the case of optimising nitrogen input in sugar beet. Eur J Agron 19:251–264

Dohleman FG, Heaton EA, Arundale RA, Long SP (2012) Seasonal dynamics of above- and below-ground biomass and nitrogen partitioning in *Miscanthus*×*giganteus* and *Panicum virgatum* across three growing seasons. GCB Bioenergy 4:534–544

Duncan WG, Loomis RS, Williams WA, Hanau R (1967) A model for simulating photosynthesis in plant communities. Hilgardia 38:181–205

Duru M, Ducrocq H, Tirilly V (1995) Modeling growth of cocksfoot (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinacea* Schreb.) at the end of spring in relation to herbage nitrogen status. J Plant Nutr 18:2033–2047

Earl HJ, Davis RF (2003) Effect of drought stress on leaf and whole canopy radiation use efficiency and yield of maize. Agron J 95:688–696

Eckersten H, Hansson PE, Johnsson H (1998) SOILN model user's manual, version 9.2. Swedish University of Agricultural Science, Uppsala, p 113

Eickhout B, Bouwman AF, Zeijts VH (2006) The role of nitrogen in world food production and food sustainability. Agric Ecosyst Environ 116:4–14

Elser JJ, Bracken ME, Cleland EE, Gruner DS, Harpole WS, Hillebrand H, Ngai JT, Seabloom EW, Shurin JB, Smith JE (2007) Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol Lett 10:1135–1142

FAO (2019) FAOSTAT Fertilizers domains, www.fao.org/faostat/en/, www.fao.org/faostat/en/, www/fao.org/faostat/en/

Farias CHA, Fernandes PD, Azevedo HM, Dantas Neto J (2008) Growth indices of irrigated and non-irrigated sugar cane in Paraiba, Brazil. Rev Bras Eng Agrı́c Ambient 12(4):356–362

Fischer RA (1993) Irrigated spring wheat and timing and amount of nitrogen fertilizer. II. Physiology of grain yield response. Field Crops Res 33:57–80

Franco HCJ, Trivelin PCO, Faroni CE, Otto R (2010) Stalk yield and technological attributes of planted cane as related to nitrogen fertilization. Sci Agric 67(5):579–590

Franko U (1996) Modelling approaches of soil organic matter turnover within the CANDY system. In: Powlson DS, Smith P, Smith JU (eds) Evaluation of soil organic matter models using existing, long-term datasets Vol. NATO ASI Series I. Springer-Verlag, Heidelberg, pp 247–254

Gallagher JN, Biscoe PJ (1978) Radiation absorption, growth and yield of cereals. J Agric Sci (Cambridge) 91:47–60

Galloway JN, Cowling EB (2002) Reactive nitrogen and the world: 200 years of change. Ambio 31:64–71

Geiger DR (1976) Effects of translocation and assimilate demand on photosynthesis. Can J Bot 54:2337–2345

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lwarence W, Muir JF, Preety J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818

Goudriaan J (1977) Crop micrometeorology: a simulation study. In: Simulation Monographs. Pudoc, Wageningen

Grant RE (1997) Changes in soil organic matter under different tillage and rotation: mathematical modeling in ecosystems. Soil Sci Soc Am J 61:1159–1174

Grant RE (2001) A review of Canadian ecosystem model- ecosystems. In: Shaffer MJ et al (eds) Modeling carbon and nitrogen dynamics for soil management. CRC Press, Boca Raton, FL

Gregersen PL, Holm PB, Krupinska K (2008) Leaf senescence and nutrient remobilisation in barley and wheat. Plant Biol 10(Suppl 1):37–49

Guretzky J, Biermacher J, Cook B, Kering M, Mosali J (2011) Switchgrass for forage and bioenergy: harvest and nitrogen rate effects on biomass yields and nutrient composition. Plant Soil 339:69–81

Hall AJ, Connor DJ, Sadras VO (1995) Radiation-use efficiency of sunflower crops: effects of specific leaf nitrogen and ontogeny. Field Crops Res 41:65–77

Hammer GL, Wright GC (1994) A theoretical analysis of nitrogen and radiation effects on radiation use efficiency in peanut. Aust J Agric Res 45:575–589

Hammer GL, Sinclair TR, Chapman SC, van Oosterom E (2004) On systems thinking, systems biology, and the in silico plant. Plant Phys 134:909–911

Himelblau E, Amasino RM (2001) Nutrients mobilized from leaves of *Arabidopsis thaliana* during leaf senescence. J Plant Physiol 158:1317–1323

Hirai MY, Yano M, Goodenowe DB, Kanaya S, Kimura T, Awazuhara M, Arita M, Fujiwara T, Saito K (2004) Integration of transcriptomics and metabolomics for understanding of global responses to nutritional stresses in *Arabidopsis thaliana*. Proc Natl Acad Sci U S A 101 (27):10205–10210

Hirel B, Le Gouis J, Ney B, Gallais A (2007) The challenge of improving nitrogen use efficiency in crop plants: towards a more central role for genetic variability and quantitative genetics within integrated approaches. J Exp Bot 58(9):2369–2387

Horton P (2000) Prospects for crop improvement through the genetic manipulation of photosynthesis: morphological and biochemical aspects of light capture. J Expl Bot 51:475–485

Howell TA, Meek DW, Hatfield JL (1983) Relationship of photosynthetically active radiation to shortwave radiation in the San Joaquin Valley. Agric Meteorol 28:157–175

Jamieson PD, Martin RJ, Martin GS, Wilson DR (1995) Drought effects on biomass production and radiation-use efficiency in barley. Field Crops Res 43:77–86

Jibran R, Hunter DA, Dijkwel PP (2013) Hormonal regulation of leaf senescence through integration of developmental and stress signals. Plant Mol Bio 82:547–561

Johnson J, Wilhelm WW, Karlen DL, Archer DW, Weinhold B, Lightle DT, Laird D, Baker J, Ochsner TE, Novak JM, Halvorson AD (2010) Nutrient removal as a function of corn Stover cutting height and cob harvest. Bio Energy Res 3:342–352

Jones JW, Tsuji GY, Hoogenboom G, Hunt LA, Thornton PK, Wilkens PW, Imamura DT, Bowen WT, Singh U (1998) Decision support system for agrotechnology transfer DSSAT v3. In: Tsuji GY, Hoogenboom G, Thornton PK (eds) Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, pp 157–177

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017a) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in indo-Gangetic Plains of India. J Curr Microbiol Appl Sci 6(3):152–163

Kakraliya SK, Kumar N, Dahiya S, Kumar S, Yadav DD, Singh M (2017b) Effect of integrated nutrient management on growth dynamics and productivity trend of wheat (*Triticum aestivum* L.) under irrigated cropping system. J Plant Devel Scie 9(1):11–15

Kakraliya SK, Kumar S, Kakraliya SS, Choudhary KK, Singh LK (2018a) Remedial options for the sustainability of rice-wheat cropping system. J Pharmacol Phytochem 7(2):163–171

Kakraliya SK, Singh U, Bohra A, Choudhary KK, Kumar S, Meena RS, Jat ML (2018b) Nitrogen and legumes: a meta-analysis. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 277–314. https://doi.org/10.1007/978-981-13-0253-4_9

Kätterer T, Andrén O, Pettersson R (1998) Growth and nitrogen dynamics of reed canary grass (*Phalaris arundinacea* L.) subjected to daily fertilization and irrigation in the field. Field Crops Res 55:153–164

Keating BA, Carberry PS, Bindraban PS, Asseng S, Meinken H, Dixon J (2010) Eco-efficient agriculture: concepts, challenges, and opportunities. Crop Sci 50(S-1):109

Kemanian AR, Stockle CO, Huggins D (2004) Variability of barley radiation-use efficiency. Crop Sci 44:1662–1672

Kering MK, Butler TJ, Biermacher JT, Guretzky JA (2012) Biomass yield and nutrient removal rates of perennial grasses under nitrogen fertilization. Bio Energy Res 5:61–70

Kersebaum KC (1989) Die simulation der Stickstoffdynamik von AckerbOden. (In German) Ph.D. dissertation, University of Hannover

Kichey T, Hirel B, Heumez E, Dubois F, Le Gouis J (2007) In winter wheat (*Triticum aestivum* L.), post-anthesis nitrogen uptake and remobilization to the grain correlates with agronomic traits and nitrogen physiological markers. Field Crops Res 102:22–32

Kiniry JR, Landivar JA, Witt M, Gerik TJ, Cavero J, Wade LJ (1998) Radiation-use efficiency response to vapour pressure deficit for maize and sorghum. Field Crops Res 56:265–270

Kiniry JR, Tischler CR, Van Esbroeck GA (1999) Radiation use efficiency and leaf CO_2 exchange for diverse C_4 grasses. Biomass Bioenergy 17:95–112

Kiniry JR, Simpson CE, Schubert AM, Reed JD (2005) Peanut leaf area index, light interception, radiation use efficiency, and harvest index at three sites in Texas. Field Crops Res 91:297–306

Koffi D, Vincent B, Valere M (2016) Yield and nitrogen use efficiency of aromatic rice varieties in response to nitrogen fertilizer. Emir J Food Agric 28:126–135

Kumar S, Sheoran S, Kakraliya SK, Kumar P, Meena RS (2016) Drought: A challenge for Indian farmers in context to climate change and variability. Progress Res Int J 11(Special-IX):6243–6246

Kumar S, Karaliya SK, Chaudhary S (2017a) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. J Curr Microb Appl Sci 6 (3):142–151

Kumar S, Singh MK, Meena RS, Hingonia K (2017b) Influence of crop geometry and cultivars on growth, yield and production efficiency of dry direct-seeded rice (*Oryza sativa* L.). J Appl Nat Sci 9(4):2469–2476

Kumar S, Meena RS, Lal R (2018) Role of legumes in soil carbon sequestration. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Berlin, pp 109–138. https://doi.org/10.1007/978-981-13-0253-4_4

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, Berlin, pp 337–375. https://doi.org/10.1007/978-981-13-7264-3_10

Ladha JK, Chakraborty D (2016) Nitrogen and cereal production: Opportunities for enhanced efficiency and reduced N losses. In: Proceedings of the 2016 International nitrogen initiative conference, 'solutions to improve nitrogen use efficiency for the world'. Melbourne, Australia. http://www.ini2016.com/1715

Lawlor DW, Cornic G (2002) Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. Plant Cell Environ 25(2):275–294

Layek J, Das A, Mitran T, Nath C, Meena RS, Yadav GS, Shivakumar BG, Kumar S, Lal R (2018) Cereal+legume intercropping: An option for improving productivity and sustaining soil health. In: Meena RS, Das A, Lal R (eds) Legumes for Soil Health and Sustainable Management. Springer, Singapore, pp 347–386. https://doi.org/10.1007/978-981-13-0253-4_11

Lecoeur J, Ney B (2003) Change with time in potential radiation-use efficiency in field pea. Eur J Agron 19:91–105

Lemus R, Parrish D, Abaye O (2008) Nitrogen-use dynamics in switchgrass grown for biomass. Bio Energy Res 1:153–162

Liang C, Wang Y, Zhu Y, Tang J, Hu B, Liu L, Ou S, Wu H, Sun X, Chu J, Chu C (2014) OsNAP connects abscisic acid and leaf senescence by fine-tuning abscisic acid biosynthesis and directly targeting senescence-associated genes in rice. Proc Natl Acad Sci USA 111:10013–10018

Lim PO, Kim HJ, Nam HG (2007) Leaf senescence. Annu Rev Plant Biol 58:115–136

Lindquist JL, Arkebauer TJ, Walters DT, Cassman KG, Dobermann A (2005) Maize radiation use efficiency under optimal growth conditions. Agron J 97:72–78

London JG (2005) Nitrogen study fertilizer fears of pollution. Nature 433:791

Long SP, East TM, Baker NR (1983) Chilling damage to photosynthesis in young *Zea mays*. I. Effect of light and temperature variation on photosynthetic CO_2 assimilation. J Exp Bot 34:177–188

Long SP, Zhu X, Naidu SL, Ort DR (2006) Can improvement in photosynthesis increase crop yields? Plant Cell Environ 29:315–330

Loomis RS, Connor DJ (1992) Crop ecology: productivity and management in agricultural systems. Cambridge University Press, Cambridge, p 538

Loomis RS, Williams WA (1969) Productivity and the morphology of crop stands. In: Eastin JD, Haskin FA, Sullivan CY, Van Bavel CHM (eds) Physiological aspects of crop yield. ASA, Madison, pp 27–47

Ma L, Shaffer MJ (2001) A review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. In: Shaffer MJ et al (eds) Modeling carbon and nitrogen dynamics for soil management. CRC Press, Boca Raton, FL, pp 55–102

Makino A, Osmond B (1991) Effects of nitrogen nutrition on nitrogen partitioning between chloroplasts and mitochondria in pea and wheat. Plant Physiol 96(2):355–362

Malnou CS, Jaggard KW, Sparkes DL (2008) Nitrogen fertilizer and the efficiency of the sugar beet crop in late summer. Eur J Agron 28:47–56

Mamo M, Malzer GL, Mulla DJ, Huggins DR, Strock J (2003) Spatial and temporal variation in economically optimum nitrogen rate for corn. Agron J 95:958–964

Manrique LA, Kiniry JR, Hodges T, Axness DS (1991) Dry matter production and radiation interception of potato. Crop Sci 31:1044–1049

Marcos J (2000) Simulation-based assessment of alternative crops in the dryland Pacific Northwest. PhD dissertation, Washington State University, p 171

Mariotti A (1997) Quelquesreflexions sur le cycle biogéochimique de l'azotedans les agrosystèmes. In: Lemaire G, Nicolardot B (eds) Maîtrise de l'azotedans les agrosystemes, vol 83. INRA Editions, Paris, pp 9–24

Matejek B, Huber C, Dannenmann M, Kohlpaintner M, Gasche R, Göttlein A, Papen H (2010) Microbial nitrogen-turnover processes within the soil profile of a nitrogen-saturated spruce forest and their relation to the small-scale pattern of seepage-water nitrate. J Plant Nutr Soil Sci 173:224–236

Matrorilli M, Katerji N, Rana G, Steduto P (1995) Sweet sorghum in Mediterranean climate: radiation use and biomass water use efficiencies. Ind Crop Prod 3:253–260

McGechan MB, Wu L, Shaffer MJ, Ma L, Hansen S (2001) A review of carbon and nitrogen processes in European soil nitrogen dynamics models. In: Modelling Carbon and Nitrogen Dynamics for Soil Management. Lewis Publishers, Boca Raton, pp 103–171

Meena H, Meena RS, Rajput BS, Kumar S (2016a) Response of bio-regulators to morphology and yield of cluster bean [*Cyamopsis tetragonoloba* (L.) Taub.] under different sowing environments. J Appl Nat Sci 8(2):715–718

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016b) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena H, Meena RS, Lal R, Yadav GS, Mitran T, Layek J, Patil SB, Kumar S, Verma T (2017a) Response of sowing dates and bio regulators on yield of clusterbean under current climate in alley cropping system in eastern U.P., India. Legume Rese 41(4):563–571. https://doi.org/10.18805/LR-3759

Meena RS, Gogoi N, Kumar S (2017b) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359

Meena BL, Fagodiya RK, Parjapat K, Kaledhonkar MJ, Sharma PC, Meena RS, Mitran T, Kumar S (2018a) Legume green manuring: An option for soil sustainability. In: Meena RS, Das A, Lal R (eds) Legumes for Soil Health and Sustainable Management. Springer, Singapore, pp 387–408. https://doi.org/10.1007/978-981-13-0253-4_12

Meena RS, Kumar V, Yadav GS, Mitran T (2018b) Response and interaction of Bradyrhizobium japonicum and Arbuscular mycorrhizal fungi in the soybean rhizosphere: A review. Plant Growth Regula 84:207–223

Meena RS, Kumar S, Yadav GS (2019) Soil carbon sequestration in crop production. In: Meena RS (ed) Nutrient Dynamics for Sustainable Crop Production. Springer, Singapore, pp 1–39. https://doi.org/10.1007/978-981-13-8660-2_1

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Michael Beman J, Arrigo KR, Matson PA (2005) Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. Nature 434:211–214

Miralles DJ, Slafer GA (1997) Radiation interception and radiation use efficiency of near-isogenic wheat lines with different height. Euphytica 97:201–208

Mitchell PL, Sheehy JE, Woodward FI (1998) Potential yields and the efficiency of radiation use in rice. In: IRRI Discussion Papers Series No. 32. International Rice Research Institute, Makati, p 62

Mitran T, Meena RS, Lal R, Layek J, Kumar S, Meena BL, Datta R (2018) Role of soil phosphorus on legume production. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Berlin, pp 487–510. https://doi.org/10.1007/978-981-13-0253-4_15

Monteith JL (1977) Climate and the efficiency of crop production in Britain. Philos Trans R Soc Lond Ser B Biol Sci 281(980):277–294

Monteith JL (1978) Reassessment of maximum growth rates for C_3 and C_4 crops. Exp Agric 14:1–5

Monteith JL (1994) Principles of resource capture by crop stands. In: Monteith JL, Scott RK, Unsworth MH (eds) Resource capture by crops. Nottingham University Press, Loughborough, pp 1–16

Monteith JL, Unsworth MH (2008) Principles of environmental physics, 3rd edn. Academic Press, London

Moore KJ, Moser LE, Vogel KP, Waller SS, Johnson BE, Pedersen JF (1991) Describing and quantifying growth stages of perennial forage grasses. Agron J 83:1073–1077

Mott KA, Parkhust DF (1991) Stomatal response to humidity in air and helox. Plant Cell Environ 14:509–515

Muchow RC, Evensen CI, Osgood RV, Robertson MJ (1997) Yield accumulation in irrigated sugarcane: II. Utilization of intercepted radiation. Agron J 89:646–652

Murchie EH, Pinto M, Horton P (2009) Agriculture and the new challenges for photosynthesis research. New Phytol 181(3):532–552

Muurinen S, Peltonen-Sainio P (2006) Radiation-use efficiency of modern and old spring cereal cultivars and its response to nitrogen in northern growing conditions. Field Crops Res 96:363–373

Nassi o Di Nasso N, Roncucci N, Triana F, Tozzini C, Bonari E (2011) Seasonal nutrient dynamics and biomass quality of giant reed (*Arundo donax* L.) and miscanthus (*Miscanthus*×*giganteus* Greef et Deuter) as energy crops. Italian J Agron 6:e24

Nassi o Di Nasso N, Roncucci N, Bonari E (2013) Seasonal dynamics of aboveground and belowground biomass and nutrient accumulation and remobilization in giant reed (*Arundo donax* L.): a three-year study on marginal land. Bio Energy Res 6:725–736

Noodén LD, Penney JP (2001) Correlative controls of senescence and plant death in *Arabidopsis thaliana* (Brassicaceae). J Exp Bot 52:2151–2159

Otto R, Franco HCJ, Faroni CE, Vitti AC, Trivelin PCO (2009) Sugarcane root and shoot phytomass related to nitrogen fertilization at planting. Pesq Agropec Bras 44(4):398–405

Paul MJ, Foyer CH (2001) Sink regulation of photosynthesis. J Exp Bot 52(360):1383–1400

Paul MJ, Peliny TK (2003) Carbon metabolite feedback regulation of leaf photosynthesis and development. J Exp Bot 54:539–547

Peltonen J, Virtanen A, Haggrèn E (1995) Using a chlorophyll meter to optimize nitrogen fertilizer application for intensively-managed small-grain cereals. J Agron Crop Sci 174:309–318

Plenet D, Mollier A, Pellerin S (2000) Growth analysis of maize field crops under phosphorus deficiency. II. Radiation use efficiency, biomass accumulation and yield components. Plant Soil 224:259–272

Prado RM, Franco CF, Puga AP (2010) Macronutrient deficiencies in soybean cv. BRSMG 68 (Vencedora) cultivated in nutritive solution. Commun Sci 1(2):114–119

Propheter JL, Staggenborg S (2010) Performance of annual and perennial biofuel crops: nutrient removal during the first two years. Agron J 102:798–805

Rani K, Sharma P, Kumar S, Wati L, Kumar R, Gurjar DS, Kumar D, Kumar R (2019) Legumes for sustainable soil and crop management. In: Meena RS, Kumar S, Bohra JS, Jat ML (eds) Sustainable management of soil and environment. Springer, Berlin, pp 193–215. https://doi.org/10.1007/978-981-13-8832-3_6

Rapp YG, Ransbotyn V, Grafi G (2015) Senescence meets dedifferentiation. Plan Theory 4:356–368

Rasmusson DC (1991) A plant breeder's experience with ideotype breeding. Field Crops Res 26:191–200

Raun WR, Johnson GV (1999) Improving nitrogen use efficiency for cereal production. Agron J 91:357–363

Reynolds MP, van Ginkel M, Ribaut JM (2000) Avenues for genetic modification of radiation use efficiency in wheat. J Exp Bot 51:459–473

Ritchie JT, Godwin DC, Otter-Nacke S (1985) CERES wheat: a simulation model of wheat growth and development. Texas A and M UnivPress, College Station

Rizzalli RH, Villalobos FJ, Orgaz F (2002) Radiation interception, radiation-use efficiency and dry matter partitioning in garlic (*Allium sativum* L.). Eur J Agron 18:33–43

Robinson N, Gamage H, Whan A, Fletcher A, Brackin R, Holst J, Lakshamanan P, Silva LCF, Casagrande JC (1983) Mineral nutrition of sugarcane (macronutrients). In: Orlando Filho J (ed) Nutrition and fertilization of sugarcane. Piracicaba, São Paulo

Rochette P, Desjardins RL, Pattey E, Lessard R (1995) Crop net carbon dioxide exchange rate and radiation use efficiency in soybean. Agron J 87:22–28

Rochette P, Desjardins RL, Pattey E, Lessard L (1996) Instantaneous measurement of radiation and water use efficiencies of a maize crop. Agron J 88:627–635

Rockström J, Steffen W, Noone K, Persson A, Chapin FS III, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B (2009) Planetary boundaries: exploring the safe operating space for humanity. Eco Society 14:32

Rodriguez D, Sadras VO (2007) The limit to wheat water-use efficiency in eastern Australia. I. Gradients in the radiation environment and atmospheric demand. Aust J Agric Res 58:287–302

Rodriguez D, Andrade FH, Goudriaan J (2000) Does assimilate supply limit leaf expansion in wheat grown in the field under low phosphorus availability? Field Crops Res 67:227–238

Rosenthal WD, Gerik TJ (1991) Radiation use efficiency among cotton cultivars. Agron J 83:655–658

Ross J (1975) Radiative transfer in plant communities. In: Monteith JL (ed) Vegetation and the Atmosphere, vol 1. Academic Press, London, pp 13–55

Sadras VO (2002) Interaction between rainfall and nitrogen fertilization of wheat in environments prone to terminal drought: economic and environmental risk analysis. Field Crops Res 77:201–215

Sadras VO, Roget DK (2004) Production and environmental aspects of cropping intensification in a semiarid environment of South Eastern. Aust Agron J 96:236–246

Sadras VO, Whitfield DM, Connor DJ (1991) Transpiration efficiency in crops of semi-dwarf and standard height sunflower. Irrig Sci 12:87–91

Sadras VO, O'Leary GJ, Roget DK (2005) Crop responses to compacted soil: capture and efficiency in the use of water and radiation. Field Crops Res 91:131–148

Satpal Tokas J, Kumar A, Kumar R (2018) Potential productivity and radiation use efficiency of multi-cut forage Sorghum. J Agromet 20:364–367

Scharf PC, Lory JA (2002) Calibrating corn color from aerial photographs to predict sidedress nitrogen need. Agron J 94:397–404

Schiltz S, Munier-Jolain N, Jeudy C, Burstin J, Salon C (2005) Dynamics of exogenous nitrogen partitioning and nitrogen remobilization from vegetative organs in pea revealed by 15N *in vivo* labeling throughout seed filling. Plant Physiol 137:1463–1473

Schmitt MR, Edwards GE (1981) Photosynthetic capacity and nitrogen use efficiency of maize, wheat, and rice: a comparison between C_3 and C_4 photosynthesis. J Exp Bot 32(3):459–466

Shaffer MJ, Delgado JA (2002) Essentials of a national nitrate leaching index assessment tool. J Soil Water Conserv 57(6):327–335

Shaffer MJ, Larson WE (1987) NTRM, a soil-crop simulation model for nitrogen, tillage, and crop residue management. Inf. Rep. 34-1.USDA-ARS Conserv

Shaffer MJ, Halvorson AD, Pierce FJ (1991) Nitrate leaching and economic analysis package (NLEAP): model description and application. In: Follett RE, Keeney DR, Cruse RM (eds) Managing nitrogen for groundwater quality and farm profitability. SSSA, Madison, pp 285–322

Shaffer MJ, Ma L, Hansen S (2001) Modeling carbon and nitrogen dynamics for soil management. In: Shaffer MJ et al (eds) Modeling carbon and nitrogen dynamics for soil management. CRC Press, Boca Raton

Sharma LK, Bali SK (2017) A review of methods to improve nitrogen use efficiency in agriculture. Sustainability (Switzerland) 10(1):1–23

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019) Growth, yield and quality of cluster bean (*Cyamopsis tetragonoloba*) as influenced by integrated nutrient management under alley cropping system. Indian J Agricul Scie 89(11):1876–1880

Sheehy JE (2000) Limits to yield for C3 and C4 rice: an agronomist's view. In: Sheehy JE, Mitchell PL, Hardy B (eds) Redesigning rice photosynthesis to increase yield. International Rice Research Institute, Los Banos, pp 39–52

Sinclair TR, Horie T (1989) Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. Crop Sci 29:90–98

Sinclair TR, Muchow RC (1999a) Radiation use efficiency. Adv Agron 65(C):215–265

Sinclair TR, Muchow RC (1999b) Radiation use efficiency. Adv Agron 65:215–265

Stahl A, Pfeifer M, Frisch M, Wittkop B, Snowdon RJ (2017) Recent genetic gains in nitrogen use efficiency in oilseed rape. Frontiers Plant Sci 8:963

Stockle CO, Debaeke P (1977) Modeling crop nitrogen requirements: a critical analysis. Eur J Agron 7:161–169

Stockle CO, Kiniry JR (1990) Variability in crop radiation use efficiency associated with vapor pressure deficit. Field Crops Res 25:171–181

Stone PJ, Wilson DR, Reid JB, Gillespie RN (2001) Water deficit effects on sweet corn. I. Water use, radiation use efficiency, growth, and yield. Aust J Agric Res 52:103–113

Sutton MA, Oenema O, Erisman JW, Leip A, van Grinsven H, Winiwarter W (2011) Too much of a good thing. Nature 472:159–161

Trapani N, Hall AJ, Sadras VO, Vilella F (1992) Ontogenetic changes in radiation use efficiency of sunflower (*Helianthus annuus* L.) crops. Field Crops Res 29:301–316

Tripathi AM, Pohankova E, Fischer M, Orsag M, Trnka M, Klem K, Marek MV (2018) The evaluation of radiation use efficiency and leaf area index development for the estimation of biomass accumulation in short rotation poplar and annual field crops. Forests 9(4):168

Uauy C, Distelfeld A, Fahima T, Blechl A, Dubcovsky J (2006) A NAC gene regulating senescence improves grain protein, zinc, and iron content in wheat. Science 314:298–1301

Valladares F, Pearcy RW (1997) Interactions between water stress, sun-shade acclimation, heat tolerance and photoinhibition in the sclerophyll *Heteromeles arbutifolia*. Plant Cell Environ 20:25–36

Van Oosterom EJ, O'Leary GJ, Carberry PS, Craufurd PQ (2002) Simulating growth, development, and yield of tiller-ing pearl millet. III. Biomass accumulation and partitioning. Field Crops Res 79:85–106

Vinod K, Rawat AK, Rao DLN (2016) Influence on soil carbon and nitrogen content in vertisols of Madhya Pradesh under different crop rotation. Q Res J Plant Anim Sci/Bhartiya Krishi Anusandhan Patrika 31:108–113

Volpe V, Giovannetti M, Sun XG, Fiorilli V, Bonfante P (2016) The phosphate transporters LjPT4 and MtPT4 mediate early root responses to phosphate status in non mycorrhizal roots. Plant Cell Environ 39:660–671

Wagenet RJ, Hutson LL (1989) LEACHM: leaching estimation and chemistry model- a process based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Water Resource Institute, Cornell University, Ithaca

Wang Q, Sun D, Hao H, Zhao X, Hao W, Liu Q (2015) Photosynthetically active radiation determining yields for an intercrop of maize with cabbage. Eur J Agron 69:32–40

Warren Wilson J (1967) Ecological data on dry-matter production by plants and plant communities. In: Bradley EF, Denmead OT (eds) The collection and processing of field data. Interscience Publishers, New York, pp 77–123

Williams JR, Dyke PT, Jones CA (1983) EPIC - A model for assessing the effects of erosion on soil productivity. In: Lauenrroth WK et al (eds) Proc. Int. Conf. on state of the art in Ecol. modeling, 4th, Colorado State Univ. 24–28 May 1982. Elsevier Scientific, New York, pp 555–572

Yang J, Worley E, Wang M, Lahner B, Salt D, Saha M, Udvardi M (2009) Natural variation for nutrient use and remobilization efficiencies in switchgrass. Bioenergy Res 2:257–266

Zoubek G, Nygren A (2008) Giving proper nitrogen credit for legumes in corn and milo rotations. Crop News Arch:1–3

Nitrogen and Phosphorus Use Efficiency in Agroecosystems

7

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Abstract

Nitrogen (N) and phosphorus (P) are two significant macronutrients for the growth and development of the plant. These two nutrients represent the highest percentage of fertilizer manufacturing and consumption in the agriculture sector. Though applied in versatility, N and P are subjected to huge losses in terms of fixation, leaching and volatilization. Nitrogen and P fertilizers have a net efficiency of 30–35%, and 18–20%, respectively. To cope with this issue, many advances have been made in terms of N sources and application methods. From split application to coating, and using nitrification inhibitors to minimize its losses, a wide range of techniques are reported. Application of organic amendments also contributes to net stabilization of N in the soil for a longer period. For coping with P losses, phosphatic fertilizers having an acidic residual effect is preferred in alkaline soil, along with indigenous P solubilization, slow-release P fertilizer modulation and use of coated fertilizers are some prominent options. Use of plant growth-promoting rhizobacteria (PGPR) to ensure sustainable N and P availability, uptake and utilization in crop plants are being advocated in this context. This chapter is an effort to comprehensively explain sources and fates of N and P in soil with special emphasis on modern ways and techniques for better management of these resources in agriculture.

Keywords

Agroecosystem · Fixation · Nitrogen · Nitrogen use efficiency · Phosphorus

Abbreviations

μg	Microgram
Al	Aluminium
AMF	Arbuscular mycorrhizal fungi
BNF	Biological nitrogen fixation
Ca	Calcium
CDU	Crotonylidene di-urea
cm	Centimetre
DAP	Diammonium phosphate
DPR	Dolomite phosphate rock
FC	Filter cake coated MAP
Fe	Iron
FYM	Farmyard manure
g	Gram
ha	Hectare
IBDU	Isobutylidene di-urea
kg	Kilograms
MAP	Monoammonium phosphate
Mg	Magnesium
MMT	Million metric tons
MPP	Monopotassium phosphate
Mt	Metric tons
N	Nitrogen
N_2O	Nitrous oxide
NBP	Nitrogen broadcast application
NBPT	N-(n-butyl) thiophosphoric triamide
NDP	Nitrogen deep placement
NH_3	Ammonia
NH_4^+	Ammonium
NO_3^-	Nitrate
NPK	Nitrogen, phosphorus, potassium
NRE	Nitrogen recovery efficiency
NUE	Nitrogen use efficiency
P	Phosphorus
PCU	Polymer-coated urea
PGPR	Plant growth-promoting rhizobacteria
PM	Poultry manure
POL	Polymer-coated MAP
PUE	Phosphorus use efficiency
RP	Rock phosphate
RZF	Root zone fertilization
SC	Compost coated MAP
SCU	Sulphur coated urea

SRF	Slow-release fertilizers
Tg	Tera-grams
TSP	Triple superphosphate
UF	Urea-formaldehyde
WSF	Water soluble fertilizers

7.1 Introduction

Sustainable food production that can meet the demand of the growing population is one of the biggest challenges of the twenty-first century (Tilman et al. 2002). A wide range of nutrients is being sufficiently applied into agroecosystem around the globe out of which phosphorus (P) and nitrogen (N) are of esteem importance. Both nutrients are a structural and integral part of the plant and human body making them the inevitable ones which must be applied exogenously in agriculture fields to get sustainable yield. Nitrogen in its available forms can be up taken from the soil and assimilated into plant body via various mechanisms (Vidal et al. 2014; Waqar et al. 2014) and can act as limiting nutrient for plants (Glass 2003; Waqar et al. 2014). Regardless of extreme importance and extensive application of N fertilizers in the agriculture sector, nitrogen use efficiency (NUE) is of major concern as it ranks in-between 30 and 35% around the globe because of the great variability in NUE determining parameters; efficiency of plants to utilize N, the efficiency of plants to uptake N and N harvest index (Ciampitti and Vyn 2013; Meena et al. 2018, 2020; Kakraliya et al. 2017). Over the last 50 years, an increase in the crop yields is less than threefolds, while the fertilizer application has increased tenfolds (Tilman et al. 2002; Verzeaux et al. 2017). This shows a considerable decrease in NUE over the period. The uncontrolled, non-stoichiometric and irregular application of N fertilizers without considering soil pool chemistry and plant needs lead to major flaws in NUE (Fageria and Baligar 2005). Extensive and uncontrolled application of N fertilizers is not only an economically unfit practice but also can leave long-lasting effects on the biosphere with the ultimate effects on humans (Hirel et al. 2007: Waqar et al. 2014). Nitrogen fertilizer application following other nutrients is the need of the hour to maintain a consistent and sustainable supply of N for sustainable agriculture production worldwide (Robertson and Groffman 2009). To reduce the losses of N, slow or controlled-release fertilizers are considered as a promising tool (Bedmar et al. 2005). Slow-release fertilizers (SRF) release N for several weeks, unlike the conventional fertilizers. Several products consist of low water-soluble compounds, urease and nitrification inhibitors which release N slowly after microbial or chemical decomposition. Tian et al. (2016) reported that the use of controlled-release fertilizer (CRF) increased the NUE (13.66%) and yield of rapeseed (*Brassica napus* L.) (12.37%) as compared to conventional fertilizer. Similarly, reduction in the emission of nitrous oxide (N_2O) by the use of urea-dicyandiamide was explained by Akiyama et al. (2015). However, organic amendments application such as poultry manure (PM), crop residues, farmyard manure (FYM), etc. significantly improve the soil fertility and health. It was also reported that organic amendments release nutrients more slowly as compared to inorganic fertilizers (Al-Gaadi et al. 2019). It was reported that 240 μg N g^{-1} (μg—microgram; g—gram) of soil was released in clover amended soil followed by 76–100 μg N g^{-1} of soil in manure and compost amended soil during a 97 days incubation experiment (Masunga et al. 2016). Apart from different fertilizer amendments, biological nitrogen fixation (BNF) is correspondingly very helpful in enhancing NUE and crop N demands. The BNF is a process in which microorganisms of different species use enzymes such as nitrogenase and convert the unavailable atmospheric N_2 to the plant-available forms (Varley et al. 2015). The exponential increase in NUE was reported with an increase in BNF (Islam and Adjesiwor 2017). The BNF of about 465, 452 and 102 kg (kilograms) N ha^{-1} $year^{-1}$ was reported by alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.), respectively (Islam and Adjesiwor 2017).

After N, P is an essential nutrient needed for proper growth of the plants and is subjected to a wide range of issues in agroecosystem from its rock reserves limitation to its least availability and higher fixation in soil (Hammond et al. 2009; Hasan et al. 2016). Due to the wide range of environmental constraints, current phosphorus use efficiency (PUE) rarely exceeds 25% and mainly falls in-between 18 and 20% worldwide (Syers et al. 2008; Mitran et al. 2018). The limiting constraints derived pressure become worse when a consistent supply of P to plants become inevitable for plant growth and sustainable yield production. Global P reserves are shrinking at a very fast rate with little-to-no renewability thus making smart use of P reserves inevitable (Roberts and Johnston 2015). At the current rate of consumption, rock phosphate (RP) reserves can be depleted within two to four centuries depending upon the cost, demand–supply relation, exploration of the reserves, future technological development and other factors (Kauwenbergh and Hellums 1995; Scholz and Wellmer 2013). The only way for increasing the life of current P reserves is the smart use of P fertilizers. It was reported that the use of SRF of P (Struvite) significantly enhanced the PUE as compared to conventional P fertilizers (Talboys et al. 2016). Several coating materials such as oil, polyethylene, latex, sulphur, polyvinyl chloride and other chemically synthesized compounds have been used to formulate SRF fertilizers (Xiang et al. 2008). Teixeira et al. (2016) used the organic acid-coated SRF of P. Results showed a significant recovery of P (+41%) by maize (*Zea mays* L.) as compared to conventional fertilizer. The addition of organic amendments enhanced the P nutrition and use efficiency. Luo et al. (2018) reported about 48% P acquisition by wheat crop (*Triticum aestivum* L.) from the soil with organic amendments. In the case of phosphatic fertilizers method of application significantly influenced the P use efficiency and the P availability to the crops. Applied P showed higher fixation and precipitation problems in the soil. A significant increase in wheat crop yield was recorded by side dressing of P fertilizer compared to the conventional broadcast method (Ali et al. 2012).

Use of biofertilizer or the microbial inoculants is also an important strategy to enhance the nutrient use efficiency. Many of the microbial inoculants can also act as biofertilizers because they can make nutrients accessible such as P and N from soil unavailable pools, from organic amendments, they can also fix N, improve the drought and salt tolerance of crops, improve the health of plants by reducing the disease incidence (Arora et al. 2013). Potential of arbuscular mycorrhizal fungi (AMF) and PGPR as biofertilizer is a well reported (Berruti et al. 2016; Rubin et al. 2017).

A small increase in P and N use efficiency can lead to long-lasting, huge economic and environmental benefits worldwide. Aiming to the great need of N and P in crop production with enormous application rate and various drawbacks in current application techniques leading to their wastage. The current chapter is an effort to summarize sources, fate and provide an overview of potential ways to enhance N and P use efficacies and increase their availability for agroecosystems.

7.2 Sources and Fate of Nitrogen and Phosphorus in the Environment

Application of N and P fertilizer was one of the major contributors to the green revolution aiming to produce enough food to feed the world. Among sources of N, plant and animal residues (Neff et al. 2002) and synthetically produced nitrogenous fertilizers using atmospheric N and natural gas (Mackenzie 1998; Galloway et al. 2013) are important. Nitrogen being an integral part of plant and animal bodies can make its way back in the form of plant residues and animal remains into the soil. Phosphorus in the soil is also present as organic and inorganic forms (Tomar 2003; Rosling et al. 2016). Organic forms of N and P does not contribute to the plant-available pool unless it gets decomposed and changed to inorganic ionic forms which can be taken up by crop plants. Inorganic forms of N and P readily available but are subjected to various constraints leading to their wastages like N leaching, fixation and volatilization, and P fixation in soil.

7.2.1 Nitrogen

The atmosphere contains about 79% of N, which is not available to plants as plants only uptake N when it is in nitrate (NO_3^-) or ammonium (NH_4^+) forms (Näsholm et al. 2009). Nitrogen added to the soil through several sources like fertilizers, crop residues, animal manures, natural fixation of N and sewage sludge is ultimately changed to mineral constituents and taken up by plants. Nitrogen mineralization, nitrification, denitrification and fixation are important domains of N cycle controlling its availability in soil (Ghaly and Ramakrishnan 2015).

7.2.1.1 Natural Sources of Nitrogen

Atmospheric N_2 needs to be converted into plant-available forms *via* breaking the strong triple bond ($N{\equiv}N$) requiring a lot of energy (Schlögl 2008) which can be provided by industrial and biological N fixation (Robertson and Groffman 2007). Though industrial N fixation seems major contributor, biological N fixation is more important as it is economical and independently occurring in agroecosystem resulting into the fixation of 200 million tons N year^{-1} into agricultural soils (Rascio and La Rocca 2008). In biological N fixation, free-living and symbiotic bacteria use nitrogenase enzyme responsible for the conversion of elemental N into mineral (NH_4^+) form (Postgate 1998; Mosberger and Lazzaro 2008). Various microbial species present in the soil contribute to N fixation in huge amounts, out of which some lives freely, and some make relations with plants called symbiotic association. Free-living N fixing bacteria contribute to 10–320 tons N ha^{-1} (Hectare) annually while bacteria in association with plant species (symbiosis) are responsible for 13–300 tons of N fixed per ha of soil annually (Bohlool et al. 1992).

Besides biological fixation, atmospheric N may enter soil N cycle through dry and wet atmospheric deposition in organic (urea, amines protein and nucleic acid) or inorganic forms i.e. ammonia (NH_3), NH_4, nitric oxide (NO), N_2O, nitric acid (HNO_3) and NO_3. Dry deposition is mainly caused by diffusion and wet deposition mainly happens by in-cloud developments and scavenging of below-cloud (He et al. 2010). Wet and dry atmospheric deposition contributes 11% of global N input (Whelan et al. 2013a, b). Application of organic amendments is also responsible for N contribution into the soil via mineralization process in which the most important thing is C:N ratio (carbon: nitrogen) of the amendment (Cherr et al. 2006; Fließbach et al. 2007; Whelan et al. 2013a, b).

7.2.1.2 Synthetically Produced Nitrogenous Fertilizers

Mineral fertilizers are a chief source of N for plant growth in current exhaustive agricultural practices in which soil indigenous N fixing capacity cannot surpass N losses from the soil. A wide range of nitrogenous fertilizers are available to be used including anhydrous ammonia (NH_3), ammonium sulphate [$(NH_4)_2SO_4$], calcium ammonium nitrate [$Ca(NO_3)_2$ $NH_4{\cdot}NO_3$], and mixed N-P fertilizers such as di-ammonium phosphate [$(NH_4)_2HPO_4$] and monoammonium phosphate ($NH_4H_2PO_4$) (Whalen and Sampedro 2010). Industrially derived N fertilizers always use the basic mechanism of the Haber–Bosch process which involve the conversion of molecular N into NH_4 forms (Vojvodic et al. 2014). In the time of utmost need, inorganic N fertilizers act as quick supplementation when applied in agricultural fields at agronomic rates generally less than 200 kg N ha^{-1} (Fließbach et al. 2007). The fate of N in soil upon application as mineral fertilizer is mainly dependent upon the composition of fertilizer and soil conditions (Minet et al. 2012). Nitrogen fixation, nitrification, denitrification, leaching and volatilization are major possible fates of N in soil upon application primarily depending upon fertilizer composition and indigenous physicochemical properties of soil (Ghaly and Ramakrishnan 2015).

7.2.2 Phosphorus

Phosphorus is frequently available in the environment even it is not in the top 10 elements of hydrosphere or lithosphere. In the lithosphere, it is placed at 11th position having concentration 90–200 × 10^3 MMT (Million Metric Tons) P. In the hydrosphere, it has 13th position with a rough estimation of the P reserves of 80–120 × 10^3 MMT (Liu and Chen 2008). In the lithosphere, rock reserves of P are a major source of extractable P but have very less solubility and poor availability if applied untreated into the soil. The calcium phosphate apatite ($Ca_{10}PO_46X_2$), where X may indicate F (fluoride), OH (hydroxide) or Cl (chloride), fluorapatite, hydroxyapatite and chlorapatite contribute 95% for the total P of the lithosphere (Stumm 1977; Fleet et al. 2011; Korzeniowska et al. 2013). Another source of P in agroecosystem is an organic form consisting of plant and animal remains. Application of P into the soil is often accompanied by its fixation, precipitation, running off with water and immobilization making its recovery 10–30% (Brady and Weil 1999; Chien et al. 2011).

7.2.2.1 Natural Sources of Phosphorus

Out on the earth, millions of tons of phosphate reserves are presently being cited at oceans (93,000 Mt (metric tons) P), Soil (40–50 Mt P), Phytomass (570–625 Mt P) Zoomass (30–50 Mt P) and Anthropomass (30–50 Mt P) (Smil 2000). Hydrosphere P reserves are higher than that of the lithosphere, while volcanic and metamorphic contain short reserves of P element. Lithosphere P reserves although enormous (Soil 40–50 Mt P) are entirely plant unavailable (Smil 1999; Kesler et al. 2015). Since mid of the nineteenth century, we have been extracting most accessible and wealthy source of phosphate rock for industrial use and production of fertilizer to meet the crop requirements. According to an estimate in the top layer of soil (50 cm—centimetre), average P is only 0.05% (Stevenson and Cole 1999) and yields about 50 gigatons (Gt) P, or unevenly 3.75 tons P ha^{-1}. Organically fixed P (in phytates and nucleic acids) contribute up to 20–80% (Tomar 2003) of element existing in the soil and its existence naturally positively correlate with soil organic N.

7.2.2.2 Synthetic Sources of Phosphorus

There is no synthetic way to produce P without using natural mineral reserves. Conversion of natural reserves into more applicable plant fertilizer is observed in industrial manipulation of P. The current fertilizer industry initiated P compound production depends upon Liebig's law that P solubility in water will increase if bones were treated with sulphuric acid (Brock et al. 2007). Major synthetically produced phosphatic fertilizers are Monocalcium phosphate (MCP), Dicalcium phosphate (DCP), Diammonium phosphate (DAP), Monoammonium phosphate (MAP), Triple superphosphate (TSP), and Monopotassium phosphate (MPP) (Smil 2000).

Worldwide, out of total phosphate reserves, 95% are present in only 12 countries out of which America contributes 33% and China + Morocco own 66% of natural reserves while remaining 27 countries control the rest of it. There is a lot of discussion going on regarding average richness of already available RP in terms of their use as phosphatic fertilizer as only 2% or even less is being used in acidic soils directly as P fertilizer (Van Kauwenbergh 1995). For its conversion to more suitable fertilizer P, its industrial manipulation and treatments are done in almost every major P fertilizer producing country.

7.3 Concerns with Nitrogen and Phosphorus in Agriculture

Improper, unguided and unbalanced utilization of nitrogenous and phosphatic fertilizers have raised a huge concern regarding their contribution to environmental pollution. Nitrogen cycle involves the process of N transformation in the environment as NH_4-fixation, NH_3-volatilization, NO_3-leaching, runoff, denitrification, microbial mediated mineralization and fixation. Similarly, with phosphatic fertilizers, major fates are P fixation and runoff with later responsible for the process of eutrophication. Nitrogen leaching in well-irrigated lands has shown deep concerns regarding NO_3 pollution in surface and groundwater (Oenema et al. 2005), and nitrous oxide contributes to global warming (Reay et al. 2012) having the 300 times more potent than carbon dioxide (Robertson and Groffman 2009).

Phosphorus is quite different from that of the N. The long-term addition of P in agricultural lands and its loss to water bodies by runoff hasten the eutrophication and reduce crop uptake (Sharpley et al. 1995; Yang et al. 2008). Therefore, the management of P loss to water bodies must be a priority. Uptake of P by plants from chemical fertilizers and soil may be influenced by many environmental and soil factors i.e., the temperature of the soil and environment, soil compaction, moisture, aeration, pH, percentage texture, P status and other nutrients status in the soil (Munson and Murphy 1986; Hasan et al. 2016).

7.3.1 Nitrogen Gains and Losses in the Environment

Nitrogen is a complex and important element likewise carbon and oxygen in the plant and soil system. Use of N fertilizer has increased from the last 50 years and has contributed significantly to the up-gradation of the cereal production up to 40% per capita (Mosier et al. 2001). According to an estimate, synthetic N supplies around 40% of the dietary protein of the world and dependency on N fertilizer through the Haber–Bosch process will rise in the coming decades (Smil 2004). Some fates of N in the soil–plant system when it undergoes different processes are nitrous oxide formation, nitrification, leaching of NO_3 to groundwater, denitrification and volatilization in the form of NH_3 (Fig. 7.1). Nitrogen is broadly known as responsible for hypoxia (low oxygen) that changing the bio network and production of the bottom waters in a large area. In the environment, N can be removed from soil through the water and wind erosion. By water and wind erosion the top fertile layer of the soil removes and causes a reduction in soil fertility (Fageria 2002).

Leaching of inorganic N pool as NO_3 with water is a common problem in sandy type of soil and varies with climatic conditions; leaching losses in arid, semi-arid areas are negligible (Wang et al. 2014). Under extreme deficient conditions, N deficiency in agriculture soils can lead to stunted growth and decrease the productivity of crop plants (Zhu et al. 2019). Nitrogen fertilizer application method is another contributor in managing N losses in agricultural soils.

Methods like broadcasting, leave more N prone to atmospheric factors increasing chances of losses as volatilization (contributing up to 20%losses in alkaline soils),

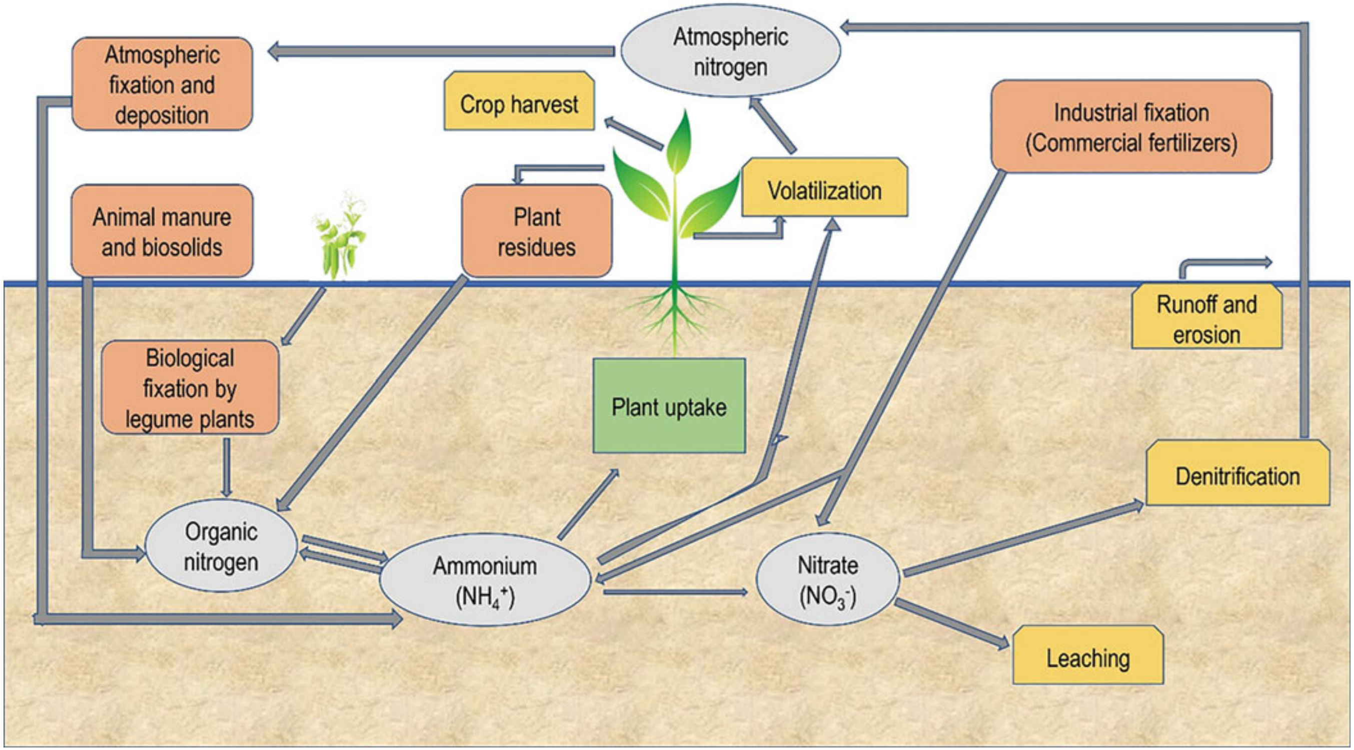

Fig. 7.1 Major nitrogen flows and stocks in agroecosystem (Source: Authors)

fixation and leaching (Fageria 2002). Soil physicochemical properties, fertilizer application methods and improper irrigation scheduling can contribute to N losses ultimately affecting plant physiology and biochemical machinery (Xu et al. 2012: Li et al. 2013).

7.3.1.1 Leaching

Aiming high solubility and mobility of NO_3^- in alkaline soil, N movement is more via mass flow thus increasing chances of losses via leaching (Jury and Nielsen 1989) degree of which is controlled by irrigation water source and availability (Meisinger and Delgado 2002). Nitrate leaching losses are more in coarse-textured soils receiving enough water necessary for net inflow/ percolation of water into the soil profile. Leaching losses of N are less in semi-arid to arid areas where net water movement is upward in the soil profile (Wang et al. 2014).

7.3.1.2 Volatilization

One of the many causes of low NUE in agroecosystems is the N volatilization in the NH_3 form. Nitrogenous fertilizers of NH_3-based composition are more prone to NH_3 volatilization if applied irregularly (Dominghetti et al. 2016; Pan et al. 2016). The leading concern for decades in agriculture is to improve the NUE of applied nitrogenous fertilizers (Chien et al. 2009). Vindicating NH_3 volatilization is immediately needed, a quantitative synthesis is lacking to assess the usefulness of mitigation strategies for NH_3 volatilization from synthetic fertilizers applied in agricultural systems (Pan et al. 2016). Smart formulation of N fertilizers having a balanced composition of NO_3 and NH_3 can be a suitable option if opted along with modern modifications to ensure long persistence of N in soil (Fan and Li 2010; Trenkel 2010). Though N volatilization is a significant cause of N loss, very little countries are working to solve this problem (Behera et al. 2013). Improper and unchecked addition of nitrogenous sources is a major cause for increased volatilization losses (Black et al. 1985; Turner et al. 2012; Bosch-Serra et al. 2014) which we can make 47–90% lower by adopting smart agriculture practices (Holcomb et al. 2011; Zaman et al. 2013; He et al. 2014).

7.3.2 Phosphorus Gains and Losses in the Environment

Various natural sources of P are present in the biosphere contributing to fulfilling P requirement for plants. In lithosphere, the soil is the most abundant and most related source of plant available P but it is subjected to various losses (Liu and Chen 2008; Liu et al. 2017) (Fig. 7.2). Some constraints regarding P availability in the soil are discussed below.

7.3.2.1 Fixation

Phosphorus fixation in agricultural soils is a well-known and established fact with various factors responsible for its (Kanwar and Grewal 1990) decreasing availability of P from exogenously applied fertilizers (Chien et al. 2012). Both chemical and

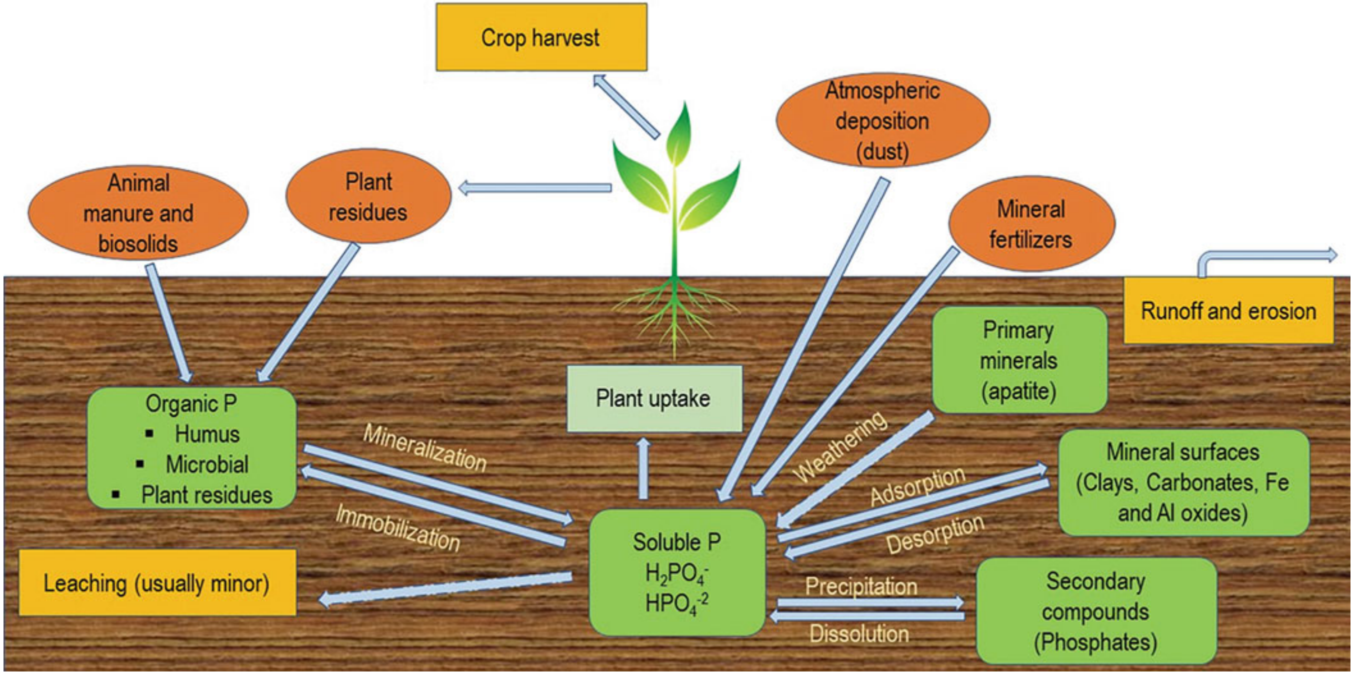

Fig. 7.2 Phosphorus gains and losses in the soil–plant system

biological (into the microbial body) fixation of P in the soil are present but chemical fixation is a dominant phenomenon. In acidic soils, P gets fixed with iron (Fe) and aluminium (Al) ions (Gerke 1992), while in alkaline calcareous soils, calcium (Ca) is the dominant cation for phosphatic precipitation (Kanwar and Grewal 1990). The labile pool of P experiences two kinds of the phenomenon on exchange sites; adsorption and desorption responsible for homeostasis of ionic phosphate in soil solution.

7.3.2.2 Adsorption-Desorption

Regarding P availability in soil, adsorption–desorption phenomenon is also quite significant in which phosphate ions are detained on exchange sites of soil (Khan et al. 2010) and/or on Al & Fe minerals (Wang et al. 2013a, b). Soil solution and exchange sites adsorption-desorption of P is of great concern regarding the maintenance of P balance in the rhizosphere (Hongshao and Stanforth 2001; Kim et al. 2002).

7.4 Enhancing Nitrogen Use Efficiency for Sustainable Agriculture

In the past few decades malpractices regarding agrochemicals have given an immense push to soil degradation (Galloway et al. 2004) and excessive N flush from agroecosystem can lead it directly to the human food chain (Robertson and Groffman 2009). Loss of N fertilizer depends on agroecosystems, characteristics of soil, application method and chemical form of fertilizer (Chen et al. 2008). The only way of decreasing nitrogenous fertilizer losses is to increase its use efficiency via adopting several modern and precision agriculture based techniques involving the use of more persistent forms and modifications in application methods.

7.4.1 Innovations in Nitrogen Sources

Nitrogenous fertilizers are highly water-soluble, and this property of N fertilizers leads to the loss of N from agricultural systems. Different physical and chemical methods can be used to reduce the solubility of N fertilizers, i.e. coating or encapsulation and the conversion of N to polymeric less soluble forms (Tables 7.1 and 7.2).

7.4.1.1 Condensation Polymers

Condensation polymers include isobutylidene di-urea (IBDU), urea-formaldehyde (UF) and crotonylidene di-urea (CDU). Urea-formaldehyde is one of the oldest slow-release N fertilizers. Urea-formaldehyde fertilizer can be produced in different forms like solid granules, suspensions, powders and liquids. Many agronomic studies provided evidence of the slow release of N from UF and UF-modified fertilizers.

Nardi et al. (2018) conducted a study to evaluate the release of N from slow-release fertilizers (SRF). Three SRF were added into the soil including CDU, UF and

Table 7.1 Effect of different nitrogen and phosphorus fertilizers and application methods on crop yields

Fertilizer type	Formulation	Application method	Increase in yield	Reference
Nitrogen	Urea	4 split application	57.8%	Belete et al. (2018a, b)
	Urea super granules (USG)	Deep placement	1.66 t ha^{-1}	Xiang et al. (2013)
	Urea	Urea deep placement (UDP)	10%	Yao et al. (2018)
	Urea-ammonium nitrate	Point-injected	0.66 t ha^{-1}	Stevens et al. (2007)
	Urea	RZF	11.5%	Jiang et al. (2018)
	Calcium nitrate [$Ca(NO_3)_2$]	Drip fertigated	1 t ha^{-1}	Danso et al. (2015)
	Urea	RZF	4.3–44.9%	Liu et al. (2016)
	Single superphosphate (SSP)	Broadcast	0.55 t ha^{-1}	Arif et al. (2010)
	Polymer-coated urea (PCU) broadcast	Subsurface band	39 kg ha^{-1}	Barker and Sawyer (2005)
	Urea	Soil application	2.14 t ha^{-1}	Alam et al. (2010)
	Urea	LN^{-1} topdressing (distances 15 cm)	3.87 t ha^{-1}	Yong et al. (2018)
	Urea	Fertilization banding placement in one side of seedling (FBPOSS)	46.15%	Bakhtiari (2014)
Phosphorus	P_2O_5	Intra-row drilling	2.03 %	Ali et al. (2004)
	Liquid (nitrophos)	Fertigation	28.95%	Alam et al. (2003)
	Polymer-coated MAP (POL)	–	3.48 t ha^{-1}	de Figueiredo et al. (2012)
	Glycerin + polymer-coated DAP	Three equal splits	3.04 t ha^{-1}	Imran et al. (2018)
	Granules (DAP)	Side dressing	49.43%	Rahim et al. (2007)

(continued)

Table 7.1 (continued)

Fertilizer type	Formulation	Application method	Increase in yield	Reference
	Controlled-release phosphorus pentoxide (P_2O_5)	Applied basal dosage	12.37%	Tian et al. (2016)
	Granules (SSP)	Fertigation	11%	Iqbal et al. (2013)
	Orthophosphoric acid (OP)	Fertigation	28%	Badr et al. (2015)
	Water-soluble monoammonium phosphate	Fertigation four times	14.17%	Li et al. (2019)
	Triple superphosphate	Foliar application	0.69 t ha^{-1}	Mosali (2004)

IBDU and treatment includes simple urea. Results indicated that N release from different fertilizers was as: UF (46–73%), urea (89–100%), CDU (44–56%) and IBDU (59–94%), respectively. Xiang et al. (2018) formulated an SRF (GSRFEx) using ammonium polyphosphate (APP), UF and amorphous silica gel (ASG) and experimented on rape crop (*Brassica* spp.). Results showed that GSRFEx is a better source to improve NUE dramatically. The efficient slow release of N was also reported by a fertilizer developed using UF nanocomposites by Yamamoto et al. (2016).

7.4.1.2 Coated Fertilizers

Coated fertilizers are made via physical or chemical coating of nitrogenous fertilizer with any desired material. In coated fertilizers, nutrient release depends on the properties of coating material, coating thickness and integrity of coating (Varadachari and Goertz 2010). Different materials like sulphur, polymers, neem oil, resins and gels, clays have been used for the coating of urea fertilizer (Tables 7.1 and 7.2).

Tong et al. (2018) experimented the evaluation of controlled release of urea on the dynamics of NO_3 and NH_4. Polyurethane coated urea and sulphur coated urea (SCU) were used. Results indicated that SCU reduced the concentration of NO_3 and NH_4, while the PCU was even more efficient than SCU. Increased nitrogen recovery efficiency (NRE) up to 60% was reported by SCU (Shivay et al. 2016). Halvorson et al. (2014) reported that nitrous oxide emission is reduced up to 42% by urea coated with polymer compared to conventional urea fertilizer. Wang et al. (2015) developed a novel polymer from recycled plastics and coated urea with that polymer at the rate of 6, 8 and 12%. Results indicated that coated urea fertilizer better met the plant N demands, reduce the volatilization and increased ^{15}N recovery. Bortoletto-Santos et al. (2020) have reported most recent accepted work in which they used coated urea using polyurethane derived from castor (*Ricinus communis*) and soybean (*Glycine max*) oil and results showed that release of urea could be controlled by varying

Table 7.2 Effect of different nitrogenous and phosphatic fertilizers on yield of different crops (% difference compared to control)

Crop	Variety	Rate of fertilizer	Type of fertilizer	% grain yield increase (%)	Reference
Wheat	Menze	360 kg ha^{-1}	Urea	302.55	Belete et al. (2018a, b)
	Ujala-2016	145 kg N ha^{-1}	Urea	196.30	Ullah et al. (2018)
	Winter wheat	150 kg N ha^{-1}	Coated urea	32.72	Fan et al. (2004)
	Yangmai 20	225 kg N ha^{-1}	Urea	3.76	Zhang et al. (2017)
	Naseer 2000	90 kg ha^{-1}	P_2O_5	21.9	Khan et al. (2007)
	Inqulab-91	81 kg ha^{-1}	P_2O_5	149.36	Rahim et al. (2010)
	Yangmai 9	108 kg ha^{-1}	P_2O_5	31.8	Zhu et al. (2012)
	Atta Habib-2010	144 mM foliar	KH_2PO_4	35	Rafiullah and Muhammad (2017)
Rice	Proagro 6207	100 kg ha^{-1}	Super Net	36.8	Chaturvedi (2005)
	BRRI Dhan-29	50% app. of N Rec. Lvl.	Biofertilizer (BRRh-5)	100	Khan et al. (2017)
	Sakha 108	220 kg N ha^{-1}	Urea	102.52	Ghoneim et al. (2018)
	Not given	60 kg P ha^{-1}	Minjingu mazao (MM)	494.9 site 1 595.5 site 2	Massawe and Mrema (2017)
	IRRI-6	90 kg ha^{-1}	P_2O_5	75	Khan et al. (2007)
	BRRI Dhan-29	50% application of the recommended level of P	Biofertilizer (BRRh-5)	100	Khan et al. (2017)
	Weiyu 64, Hybrid 78130, Dingyu, Dofu, Hybrid 428, Eyou 938, Shuanyou 2292	104 kg N, 12 kg P, 113 kg K+ 3750 kg cattle manure	NPK fertilizer + cattle manure (NPKM)	97	Lan et al. (2012)
Maize	Rampur Composite	200 kg N ha^{-1}	Urea	154.74	Shrestha (2015)

(continued)

Table 7.2 (continued)

Crop	Variety	Rate of fertilizer	Type of fertilizer	% grain yield increase (%)	Reference
	ZM 621	180 kg N ha^{-1}	Urea	44.93	Pokhrel et al. 2009)
	DEKALB C60-19	168 kg N ha^{-1}	Anhydrous ammonia + polymer-coated urea (PCU)	23	Noellsch et al. (2009)
	Elite 20T06	150 kg N ha^{-1}	Polymer-coated urea (PCU)	108	Gagnon et al. (2012)
	Single Hybrid 10	476 kg ha^{-1} and 20 t ha^{-1}	Superphosphate + FYM	44.6	El-Eyuoon and Amin (2018)
	Not given	Desired 100 kg P ha^{-1}	50:50 PM or FYM+DAP	45.8	Ali et al. (2019)
	BH 660	18.3 kg P from Tithonia + 2 kg p from TSP ha^{-1}	10% P (TSP) + 90% P (Tithonia)	79	Endris (2019)

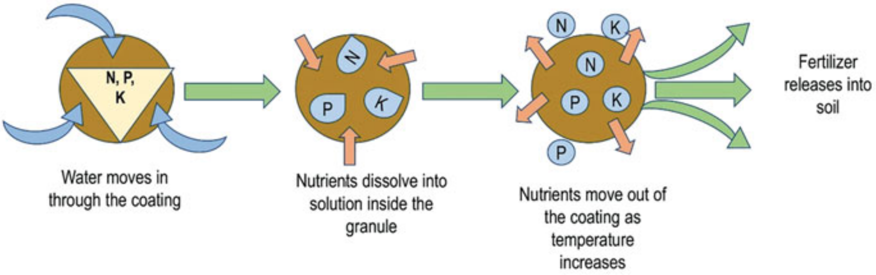

Fig. 7.3 General nutrient release mechanism of coated fertilizers

coating thickness and they also declare the better strategy to coat urea with the eco-friendly polymer. A general mechanism of the release of nutrients from a coated fertilizer is presented in Fig. 7.3.

Jadon et al. (2018) reported that NH_3 volatilization was reduced up to 27.5, and 41.1% by neem coated urea and pine oleoresin coated urea, respectively, and the leaching of NO_3-N is reduced up to 18.3, 28, 25.7 and 35.1% by neem coated, resin coated, nano-rock phosphate coated and ZnO nanoparticle (zinc oxide) coated urea, respectively.

7.4.2 Stabilized Nitrogen Products

7.4.2.1 Nitrification Inhibitors

Nitrification inhibitors have been used in agriculture to lower down the losses of N in gaseous form by slowing down the process of nitrification and to enhance the yield of the crops (Randall and Vetch 2003; Frame 2017; Ren et al. 2017). The slowdown of the nitrification process force N retention in the soil in the form of less mobile NH_4 form which ultimately reduced the leaching losses of NO_3-N (Rybárová et al. 2018).

Rybárová et al. (2018) conducted a study to evaluate the effectiveness of nitrification inhibitors in soil. In this study, a nitrogen-sulphur fertilizer ENSIN which also contains dicyandiamide and 1,2,4-triazole as nitrification inhibitors have been added. Soil analysis showed that application of ENSIN reduced the NO_3-N in soil up to 32% when added in a single dose, while the split application of ENSIN reduced NO_3-N up to 62%. Application of Dicyandiamide as a nitrification inhibitor significantly reduced nitrous oxide emissions up to 20% (Misselbrook et al. 2014). Lam et al. (2017) claimed that nitrification inhibitors reduced the direct nitrous oxide emissions up to 8–57%. Application of DCD at 5, 7 and 10 kg ha^{-1} reduced nitrous oxide emissions of 25, 47 and 47%, respectively (Zaman and Blennerhassett 2010). Very recently, Ashraf et al. (2019) reported decreased N losses via increased N recovery, improved growth and yield of maize due to applied organic materials (neem oil (*Azadirachta indica*), moringa leaf extract (*Moringa oleifera*), pomegranate extract (*Punica granatum*)) coated on urea as nitrification inhibitors.

7.4.2.2 Urease Inhibitors

One of the strategies to enhance NUE and to reduce the pollutants generated by urea hydrolysis is the use of urease inhibitors (Modolo et al. 2015; Li et al. 2017; Mira et al. 2017). Urease is an enzyme that converts urea into NH_3 and having wide distribution, it can be found in soil, plants and microbes, etc. (Follmer 2008).

Li et al. (2015) proved that application of N (propyl) thiophosphoric triamide (NPPT) along with urea reduced the NH_3 volatilization up to 50% compared to control treatment. According to (Ni et al. 2014) recently studied phosphoric triamide (2-NPT) and N-(2-nitrophenyl) as a urease inhibitor to reduce the NH_3 volatilization up to 26–83%. Cantarella et al. (2018) conducted a study using N-(n-butyl) thiophosphoric triamide (NBPT) as a urease inhibitor. Results showed that application of NBPT with urea reduced NH_3 volatilization up to 53%.

7.4.3 Innovations in Nitrogen Application Methods

Method of application of N fertilizer plays an important role in NUE (Zhu and Chen 2002; Wang et al. 2016). Inappropriate application method also leads to environmental problems like atmosphere contamination, degradation of soil quality and water pollution (Davidson 2009; Reay et al. 2012) (Table 7.1). Thus, efficient nutrient management techniques are needed to increase NUE, crop yield and to reduce environmental pollution (Guo et al. 2008; Chen et al. 2014). Efficient nutrient management techniques largely depend on application method, type of fertilizer and the rate of fertilizer addition (Cui et al. 2010; Nash et al. 2013; Zheng et al. 2017). Many researchers reported that splitting of N fertilizer dose enhances the NUE significantly and reduces the losses of N which ultimately increased the crop yield (Chen et al. 2011; Kettering et al. 2013). Wang et al. (2016) stated that recovery efficiency of N for three split and two split fertilizer application is much higher than the one-time application of whole fertilizer dose as basal dressing, this practice also reduces N losses remarkably. Recently, Yao et al. (2018) stated that N recovery efficiency has been improved up to 55%, and 91% decrease in NH_4 volatilization was recorded by deep placement at one point compared to surface split broadcasting. According to the studies conducted previously, agronomic fertilizer efficiency and crop yield by the deep placement of fertilizers are much higher compared to the conventional split application by farmers (Mohanty et al. 1998; Jiang et al. 2018). Wu et al. (2017) established a field and pot studies to access the effectiveness of nitrogen deep placement (NDP) over nitrogen broadcast application (NBP). Results indicated that NRE and grain yield of the crop were increased significantly by NDP compared to NBP. Pot experiment results showed that NDP could maintain higher N supply in 5–20 cm soil layer compared to NBP which enhances absorption of N in plants and ultimately leads to higher NRE.

It is reported that N fertilizer application in the root zone (root zone fertilization) proved a good application method to reduce N losses in rice (*Oryza sativa*) fields and wheat–soil system (Chen et al. 2016; Liu et al. 2016). Root zone fertilization (RZF) in summer maize 12 cm deep and 5 cm away from seed proved to be a good RZF method (Jiang et al. 2017). Jiang et al. (2018) experimented to evaluate the effectiveness of one-time RZF and the results showed that RZF enhanced the yield up to 7% and increased the ^{15}N recovery remarkably up to 28.7%. Reduction in N losses up to 30.2% was also recorded. According to Zenawi and Mizan (2019) placement of fertilizer 5–10 cm away and 3–5 cm deeper in soil from seed could be a better strategy.

Shrestha et al. (2018) explained that addition of N source as a basal dose and split application at critical growth stages like at knee height and flowering stage are necessary to enhance crop yield. Bakhtiari (2014) reported that band placement on one side of the seed of N fertilizer 5 cm deep and 10 cm away from seed was the best method for N application. Yong et al. (2018) also stated that NUE, N uptake and agronomic use efficiency of N significantly increased up to 12.4, 72.5 and 51.6%, respectively, by top dressing compared to the conventional application method.

7.4.4 Use of Amendments for Better Nitrogen Conservation

Organic amendments application to the soil to maintain fertility status and soil health is the soil management strategies (Killham 2011), including N which is one of the most important nutrients in low input managed farming systems. Manure, litter from animal farms, composts and green manure are considered as important soil amendments and once they mineralize than these are considered as major nutrient sources (Nin et al. 2016; Niamat et al. 2019). Soil organic matter and N are important components of soil fertility. Due to more effect on soil biological, chemical and physical properties green manure considered as a more important and effective amendment in soil fertility management by researchers, agronomists and governments globally. Nowadays we can find several opportunities to grow green manure crops on your farm like intercropping, crop rotation and cover crops (Power et al. 1986; Nin et al. 2016). Intercropping of green manures enhances NUE, increases weed control, reduce the N losses and ultimately increases the yield (Jensen et al. 2015). The additional benefit of green manure crops is that they can fix atmospheric N, which stores in organic N form and available when the residues decomposed completely (Hardy 1993). Green manures can produce biomass up to 5–9 tons ha^{-1} $year^{-1}$ which includes about 40% dry matter as carbon and about 2–4% as N (Nin et al. 2016). Different green manure crops have different N productivity like 80 kg for berseem clover to 190 kg sub clover ha^{-1} (Nin et al. 2016). Fowler et al. (2004) conducted a study to evaluate the effect of three green manure crops including oat (*Avena sativa*), lupin (*Lupinus* sp.) and oat-lupin mix on NO_3 leaching in winter and N uptake and yield of the following crop. Results indicated that winter NO_3 leaching was reduced significantly, and the N uptake and dry matter production of upcoming ryegrass crops was increased significantly. Islam et al. (2015) conducted research using different green manure crops and various N chemical fertilizers in rice. Results showed that crop growth parameters and N uptake and recovery have been increased significantly by green manure incorporated crops in rice.

Returning of crop straw after harvesting the crop to the soil is an economical, sustainable and promising approach to improve soil fertility and to sequester the carbon (Dikgwatlhe et al. 2014). Double rotation of summer maize and winter wheat is a common and intensive cropping system used in china mostly. In this system, the main focus is on the chemical fertilizers so in this condition, returning of crop stubbles to the soil is important to maintain soil fertility (Liu et al. 2014; Meena et al. 2020). Residues of the crop change the primary macro nutrient (NPK) turnover (Luxhoi et al. 2007; Damon et al. 2014). Maize crop residues act as an important component of soil N pool because they contain about 80 kg N ha^{-1} (Burgess et al. 2002), and one of the major sources of N for the upcoming crop on the farm (Álvarez et al. 2008; Akkal-corfini et al. 2010). Availability of N from crop residues in soil crop system is entirely different than chemical N fertilizers because in this case availability of N depends on the decomposition of residues (Douxchamps et al. 2011). Hu et al. (2015) applied ^{15}N labelled crop residues to soil and the results indicated that 8.4% of the N from residues was recovered in the first growing season and the major part of the remaining N (61.9–91.9%) was recovered in the upcoming seasons. The N concentration in the soil was increased up to 73.8% by sequential application of crop residues.

Animal farm manure, PM and compost products are also consisting of higher amounts of N and other nutrients as well which can reduce the demand of chemical fertilizers to maintain soil fertility (Darzi 2012). Apart from supplying nutrients like N organic manures also improve soil biological, chemical and physical properties

(Najm et al. 2012). Pitta et al. (2012) applied a different amount of PM to the soil. Results demonstrated that during the first 30 days the dry matter loss was highest and 40% of the N was released during the first 60 days. After completion of 1-year residual N of PM in soil was 27%. Yeshiwas et al. (2018) conducted a field experiment to evaluate the effectiveness of integrated use of FYM and chemical fertilizers. Amount of FYM was 0, 15 and 30 t ha^{-1} and levels of N were 0, 75 and 150 kg ha^{-1}. Results indicated that 30 t ha^{-1} FYM + 75 kg ha^{-1} N significantly increased the lettuce (*Lactuca sativa*) yield. Many scientists evaluated the effect of FYM alone and along with chemical N fertilizers and significant results of soil fertility enhancement and crop yield improvement were recorded (Shakoor et al. 2015). Addition of pig slurry composting to soil at 4, 8 and 12 Mg (Mega-gram) ha^{-1} significantly increased the growth and yield parameters of millet crop (*Pennisetum glaucum*) (da Silva Mazareli et al. 2016). Horrocks et al. (2016) added municipal compost which generally consists of 2–2.5% of N in the soil. Results demonstrated that about 13–23% of N released from compost was used by crops in 2–3 years. Niamat et al. (2019), in another study, reported increased contents and uptake of N and P in maize with the application of Ca-fortified animal manure.

7.4.5 Role of Symbiosis in Nitrogen Nutrition

Nitrogen fertilizers applied to the crops to increase food production so, in this situation, it is needed to adopt more sustainable approaches like sustainable intensification and climate-smart agriculture (Jangir et al. 2016; Meena et al. 2016). The process in which microorganisms fix atmospheric N_2 to plant-available forms using nitrogenase enzyme is called BNF (Unkovich et al. 2010; Varley et al. 2015). Before the industrial revolution, it was the main source of N to crops (Vitousek et al. 1621). Researchers agreed that BNF is the most sustainable approach and it is known that NUE is increased by increasing biologically fixed N in the soil while the application of chemical N fertilizers reduced NUE linearly (Lassaletta et al. 2014). Fixation of N which is carried out by association between seed and rhizobacteria and leguminous crops is considered as one of the major sources for the reduction of N in the agricultural system (Liu et al. 2011; Peix et al. 2015). According to the stats presented by Food and Agriculture Organisation (FAO) annual N fixation by oilseed crops were 18.5 Tg (Tera-grams) N and 2.95 Tg N by pulses (Herridge et al. 2008; Islam and Adjesiwor 2017). Contribution of biologically fixed N is 25 Tg N which is dominated by 100 Tg N by chemical fertilizers (Lassaletta et al. 2014). It is reported that nearly 80% of BNF resulted from plant–microbe (leguminous plants + *Rhizobia* sp.) symbiotic relationship (Vance 1998; Mabrouk et al. 2018). Symbiotic relation of plants with stress-tolerant rhizobia species can increase the N fixation by increasing nodulation under stressful environment (Zou et al. 1995; Mabrouk et al. 2018). Verzeaux et al. (2017) reported that conservation or no-till system increases the AMF association with plants compared to the conventional tillage system. According to studies it is reported that AMF plays an important role in the uptake of nutrients like N and P. Bücking and Kafle (2015) reported that N can be transported to the host plant by AMF. Nowadays the use of biofertilizers is increasing day by day. Biofertilizers is a material which consists of living microbes and can be applied to soil, seeds and plants and after that, those living microbes start growing in the root zone and inside of the plant body and improve plant health by increasing the nutrient supply and by suppressing diseases (Bardi and Malusà 2012; Malusá and Vassilev 2014; Ali et al. 2017). Biofertilizers play a major part in increasing fertility of the soil by fixing atmospheric N and by the production of plant growth-promoting materials (Mazid and Khan 2015). Plant growth-promoting bacteria include the microbial species which are free-living, endophytes (which colonize some plant tissues) and the species which make symbiotic associations with plants and cyanobacteria (Farrar et al. 2014).

7.5 Enhancing Phosphorus Use Efficiency for Sustainable Agriculture

7.5.1 Innovations in Phosphorus Sources

Fertilizer type is one of the main factors which influences the P availability and adsorption (Tables 7.1 and 7.2). Fertilizers which are more soluble release P in soil solution more rapidly compared to slow-released or less soluble fertilizers. Contact time of P to soil colloids directly influence the intensity of P adsorption to soil (Laboski and Lamb 2003; Stauffer et al. 2019). Currently, polymer-coated P fertilizers have been used to increase the period in which P is available to plants (Trenkel 2010). Polymer coatings on P fertilizers significantly slow down the release of P and to reduce the adsorption of P by minimizing the direct contact of fertilizers to the soil colloids (Stauffer et al. 2019). de Figueiredo et al. (2012) carried out an experiment to evaluate the effect of polymer-coated and uncoated P fertilizers on maize production and the results showed that polymer-coated fertilizers increased the maize production up to 3.48 t ha^{-1} compared to uncoated fertilizer. Imran et al. (2018) carried out a study to evaluate the effect of polymer-coated DAP, conventional DAP, glycerine coated DAP. Results indicated that polymer-coated DAP significantly increased the growth parameters and uptake of P in wheat. Similarly, Rosling et al. (2016) evaluated the performance of slow-release fertilizers by using commercial and polymer-coated MAP and DAP. Results of incubation study showed that uncoated fertilizers released the total P within 10 days of the application, while the coated P fertilizers released (MAP—77% and DAP—57%) of P in the first 45 days after application.

Another slow-release P fertilizer preparation technique is to mix the P fertilizer with organic manure (Table 7.1) or coating with an organic acid (de Castro et al. 2015). In this technique adsorption of P to soil colloids is reduced and the organic acids also protect the P in soil solution chemically by binding P around organic acid granules (Stauffer et al. 2019). It is also reported that organic acids bind with Al and Fe thus reducing P fixation to Al and Fe (Guppy et al. 2005). Stauffer et al. (2019)

conducted a study to evaluate the release of P from commercial, polymer-coated and organophosphate coated MAP. The commercial MAP, POL, filter cake coated MAP (FC) and swine compost coated MAP (SC) were used. Results showed that the release of P within 14 days of application compared to control was 54.9–54.2% SC, 83.2–84.4% FC, and 88.5–95.4% POL. So, it was estimated that coating of P fertilizers with organic materials can be a good technique to maintain the release of P with time. Teixeira et al. (2016) conducted a study using different organic acids coated MAP. They used Commercial MAP (MAP_1), MAP_2 = natural organic acid-coated, MAP_3 = synthetic organic acid-coated, MAP_4 = Peat humic organic acid-coated. Results indicated that maximum slow release was recorded with MAP_4. It was also noted that the agronomic efficiency of P is 11–13% higher in organic acid-coated fertilizers compared to commercial MAP.

Dolomite phosphate rock (DPR) containing P, Ca and magnesium (Mg) is also considered an important alternative P fertilizer in acidic sandy soils. An experiment is established by Yang et al. (2012) to evaluate the effectiveness of DPR in acidic sandy soils of Florida. They used DPR and other water-soluble fertilizers (WSF) in ryegrass (*Lolium*). It was evaluated that DPR proved to be superior compared to other WSF. DPR increased the growth and P uptake in ryegrass. It was also recorded that DPR can increase the pH of acidic soils.

It was reported that the use of P with urea can enhance P-fertilizer use efficiency (Giroto et al. 2017). Agreeing to Anstoetz et al. (2015), P fixation can be reduced by mixing phosphate with urea in a single matrix. Giroto et al. (2017) carried out a study to evaluate the availability of N and P by nanocomposite slow-release fertilizers. In this experiment, nanocomposites were produced using urea and then mixing of hydroxyapatite particles was done. Results showed that the interaction of hydroxyapatite with urea matrix released P slowly and reduced the adsorption on soil colloids.

Another natural clay mineral attapulgite is also known as palygorskite also used to coat micronutrient fertilizers. Attapulgite itself also used as a major source of micronutrient and other beneficial elements as it consists of Ca, Mg, Fe, K, manganese (Mn), Al and silicon (Si) (Xie et al. 2011a, b). Attapulgite shows some good properties like higher surface area, higher water retention capacity, high adsorption capacity and slow release of ions. Yang et al. (2010) reported that use of attapulgite along with other compound fertilizers increased the crop yields. According to Guan et al. (2014), attapulgite coated fertilizers showed slow-release behaviour and increased the crop yield by 15.1–18.4% compared to control treatment.

7.5.1.1 Application Methods of Phosphorus

There are two main categories of P application methods broadcasting and band placement (Noonari et al. 2016). Broadcast method is easy, economical and time-saving but only valuable when after broadcasting you have to cultivate the soil using cultivators of disk harrows. Broadcast method is a less efficient method of P application because in this method contact area of P fertilizer to soil colloids is greater which enhances the fixation of P to Al, Fe and Ca and reduce the availability to plants (Vance et al. 2003; Syers et al. 2008; McLaughlin et al. 2011). Phosphorus losses and environmental problems related to the placement of P fertilizers in the soil like runoff of P linked with the eutrophication of water bodies (Chien et al. 2009). But some scientists also reported that broadcast application of P to some crops is a better strategy rather than band placement. Ma et al. (2009) explained that as compared to broadcast, deep placement of P source reduce the yield of the crop and causes P deficiency at the seedling stage. Similarly, Hu (2016) stated that horizontal placement of P 12 cm away from rice seedlings cause a reduction in crop yield compared to the broadcasting of P fertilizer. Lu et al. (2018) evaluated the effectiveness of broadcast and band placement of P fertilizer. Results showed that band placement increased the yield of wheat as compared to broadcast application but the placing of P fertilizer 12 cm apart from seed reduce the P uptake and yield compared to a broadcast application.

Noonari et al. (2016) experimented to evaluate the response of two different P placement methods—drilling method and broadcast method. They concluded that drilling of P was a better method for increasing the uptake of P and the yield in comparison to conventional broadcast method. Ali et al. (2012) experimented by placing P fertilizer in different ways in wheat crop like broadcast (M1), side dressing (M2), broadcast at the time of sowing + before 1st irrigation (M3) and broadcast at 1st irrigation (M4). Results showed that side dressing of P at the time of sowing increased the fertile tillers, growth and grain yield as compared to other application methods. Duarte et al. (2019) concluded that localized application of P was a better strategy to apply P compared to a broadcast application. Tariq et al. (2012) also determined that the side dressing of P fertilizer is a better application method for increasing growth, yield and P uptake of plants.

Application of P using fertigation technique can also be a good strategy to increase crop growth and production compared to conventional application methods. Badr et al. (2015) led an experiment to evaluate the effectiveness of fertigation technique on eggplant (*Solanum melongena*). They applied P as a pre-plant application of superphosphate and fertigation of orthophosphoric acid. Results displayed that fertigation of P increased the growth of plants, increased the number of fruits and ultimately increased the overall yield of eggplants.

7.5.1.2 Use of Amendments for Better Phosphorus Conservation

Rock phosphate (RP) is the raw material used to prepare synthetic P fertilizers. Rock phosphate is a non-renewable material and it is assumed that existing reserves of RP can be depleted in 50–100 years (Cordell et al. 2009). Mainly in the agriculture sector, P application is based on mineral P fertilizers. We need to explore new fertilization strategies to maintain soil fertility and plant nutrition requirements and to produce enough food to fulfil the requirements of the growing population (Faucon et al. 2015). One of the solutions can be the recycling of P from organic wastes/products like biochar, sewage sludge, PM and crop residues (Ott and Rechberger 2012; Lwin et al. 2017). Biochar is produced by the pyrolysis of biomass material under low or no environmental oxygen (Lehmann and Joseph 2015; Placido et al. 2016). The application of biochar is reported to lower the precipitation of P with Fe and; therefore, enhanced the P availability (Cui et al. 2011). In this regard, the application of biochar at 1.0 t ha^{-1} along with mineral fertilizers gave better performance compared to mineral fertilizers alone, as concluded by Glaser et al. (2015). Recently Santos et al. (2019) used granulated biochar with TSP specified that dry matter production and P uptake was increased in maize. They also noticed the increased soil available P with this combination. Likewise, the application of compost and biochar made from pineapple waste increased the total P, available P, and their organic and inorganic fractions in the soil (Ch'ng et al. 2014). Kizito et al. (2019) added digestate enriched biochar to soil and reported that total P was increased up to 450% by corn biochar and 170% by wood biochar.

Organic wastes and sewage sludge include various forms of P including organic and inorganic fractions depending on the processes of treatments (Frossard et al. 1996). Mostly the dominant organic fractions are phytate and hexakisphosphate (Toor et al. 2006; Darch et al. 2014), while the Fe-bound, Al-bound and Ca-bound phosphates are coming under inorganic P fractions in sewage sludge (Xie et al. 2011a, b). It is needed to convert these unavailable P forms to plant-available forms. It is reported that application of organic wastes along with carbon (Mäder et al. 2002; Criquet et al. 2007) and plants itself releasing molecular signals (Schilling et al. 1998) can enhance microbial population, which ultimately increase the P acquisition. Root occupation with AMF increased the explored soil volume and also increased the uptake of nutrients like P (Ferrol et al. 2019). Recently, Nobile et al. (2019) described that barley and wheat uptake as much P from the sewage sludge applied to soil as they uptake from mineral P fertilizer, while in the case of canola crop more P was recorded in case of sewage sludge applied to soil compared to mineral P fertilizer, which was due to the release of more acids from roots to solubilize unavailable P from sewage sludge.

Poultry manure a growing waste product from poultry industry (FAO 2018) is known for its high P content (Pagliari and Laboski 2012). Use of mineral P fertilizers can be significantly reduced by applying it in its raw form or by composting it into other organic amendments (Redding et al. 2016; Calabi-Floody et al. 2018). Soil P forms and activities of phosphatase have been changed by the application of PM (Waldrip et al. 2011). The combined use of RP and PM proved to be a good strategy to meet plant nutrient requirements (Song et al. 2017). It was testified that chilli and wheat yield has been increased by the application of the mixture of PM and RP (Abbasi et al. 2013, 2015). Poblete-Grant et al. (2019) recently stated that the application of PM + RP mixture to ryegrass significantly increased the growth and P uptake.

7.6 Using Biofertilizers for Enhanced Nitrogen and Phosphorus Availability

Sustaining agricultural production without harming the conservation of natural resources and the quality of the environment are the main considerations of the modern world. The soil is a dynamic matrix that supports plant production. However, in the soil environment plant growth is hampered by various biotic and abiotic stresses, for instance, plant pathogens, weeds, salinity, drought, heavy metals, temperature and flooding conditions (Nadeem et al. 2014; Ali et al. 2017; Mustafa et al. 2019). The excessive utilization of agrochemicals to combat such stresses and recompenses the crop production losses, on the other hand, threatens environmental quality. During the last few decades, significant advances have arisen in understanding soil–microbe interactions for sustainable crop production in an economically sound and ecologically viable option. The plant rhizosphere is home to millions of bacterial species that exhibit growth-promoting effects to plants via direct and indirect mechanisms and recognized as PGPR (Kloepper et al. 1986; Zahir et al. 2004; Kumari et al. 2019). Recently PGPR have gained significant attention of the scientific community for use as biofertilizers for sustainable agricultural production (Khalid et al. 2009). Numerous experiments hitherto have explained the increased crop yield and growth via enhanced nutrient use efficiencies using PGPR-based biofertilizers. Some aspects of PGPR-based biofertilizers in enhancing N and P use efficiencies are discussed.

7.6.1 Plant Growth-Promoting Rhizobacteria and Biological Nitrogen Fixation

Nitrogen is considered as a key mineral nutrient for proper development and growth of the plants and one of the main factors affecting the crop production (Ali et al. 2017). Certain PGPR are equipped with the specialized mechanisms using nitrogenase enzyme to reduce N_2 to NH_4 through a process termed as BNF (Kim and Rees 1994; Jetiyanon 2015). The BNF is a well-studied phenomenon involved approximately two-thirds of the total N fixed globally through diazotrophic microbial communities mostly archaea and bacteria (Dixon and Kahn 2004). Nitrogen-fixing microbes are normally classified as symbiotic (rhizobium-legume/non-legume symbiosis), associative symbiotic (endophytes) and free-living (Azotobacter and Azospirillum spp.) with most of the N fixed through symbiotic N fixing mechanisms (Bashan and Levanony 1990; Zahran 2001; Bhattacharyya and Jha 2012; Kakraliya et al. 2018; Kumar et al. 2018; Layek et al. 2018; Rani et al. 2019). In this regard, symbiotic N fixers develop symbiotic relationships with legume roots and hence leguminous crops took advantage through increased supply of biologically fixed N (Ali et al. 2017; Ahmad et al. 2019; Naseer et al. 2019). However, other agriculturally important crops especially grasses such as wheat, rice, corn, etc., are unable to perform BNF and, hence there is an increasing trend of studies regarding the supply of N through PGPR-based inoculants (Charpentier and Oldroyd 2010; Chamani et al. 2015; Kamran et al. 2017; Picazevicz et al. 2017). Previously, Parmar and Dadarwal (1999) suggested increased nodulation and N fixing ability of chickpea (*Cicer arietinum*) due to inoculation of N fixing *Fluorescent pseudomonads*. In another study, regulation of BNF in soybean production due to applied Brady rhizobium spp. has been well reported (Okito et al. 2004). Very recently, Ahmad et al. (2019) testified increased growth, nodulation and N fixing ability of chickpea with the applied *Paenibacillus* spp. in a jar trial. Summary on a range of studies describing various PGPR mediated plant growth promotion *via* increased atmospheric N_2 fixation is given in Table 7.3. However, for obtaining maximum on-farm benefits from diazotrophic PGPR-based biofertilizers, a systematic strategy that allows for full utilization of all beneficial effects and increases crop yield while minimizing the chemical fertilizer inputs is therefore required (Kennedy et al. 2004).

7.6.2 Plant Growth-Promoting Rhizobacteria and Phosphorus Solubilization

Phosphorus is an essential nutrient as well as one of the main factors affecting the plant growth despite its abundance in the soil as both (inorganic and organic forms). Almost, 95–99% of P in the soil represents the insoluble pool and cannot be utilized by plants (Vassileva et al. 2000). An increasing number of strategies have been documented earlier to convert this insoluble form of P to soluble forms to facilitate plant uptake. In this regard, exploiting the potentials of rhizosphere microbiome has garnered considerable attention worldwide, especially the use of phosphate-solubilizing rhizobacteria in agriculture. These bacteria under their P solubilizing activity convert insoluble P to plant-available forms and are increasingly applied as biofertilizers for better crop production since the 1950s (Kudashev 1956; Kumawat et al. 2009; Anand et al. 2013; Samreen et al. 2019). A range of rhizosphere inhabiting bacteria has shown the ability of insoluble phosphate solubilization falling in the genera *Bacilli*, *Pseudomonas*, *Escherichia*, *Serratia*, *Achromobacter*, *Corynebacterium*, *Erwinia*, *Brevibacterium*, *Xanthomonas* and *Micrococcus* spp. However, among these all, *Bacilli* and *Pseudomonas* are the most dominant inhabitants with varying compositions in plant rhizosphere and non-rhizosphere soil (Kumawat et al. 2017). Certain commonly found PGPR are equipped with specialized mechanisms by which they can solubilize unavailable phosphates to plant-available HPO_4^- (monohydrogen phosphate ion) and $H_2PO_4^-$ (dihydrogen phosphate ion) through lowering rhizospheric pH, dissolving metal phosphate complexes by releasing organic acids and ion exchange processes, and, hence improve crop yields through enhanced nutritional availability to main crop (Kumar et al. 2014; Ali et al. 2017; Saeed et al. 2019; Ahmad et al. 2019). In addition, using PGPR exhibiting P solubilization activity as biofertilizers would not only cut down the high costs associated with mineral fertilizer application in agriculture but also improves the overall quality of the environment (Banerjee et al. 2010). Application of biofertilizers containing beneficial PGPR favours the development of beneficial communities within the rhizosphere associated with increased crop yields (Noor et al. 2020). For instance, in a study, the inoculation of PGPR showing P solubilizing activity increased plant growth and root proliferation of alfalfa plants (Guiñazú et al. 2009). Summary of studies involving the application of biofertilizers based on PGPR is given in Table 7.3.

Table 7.3 Role of different biofertilizers in nitrogen and phosphorus nutrition in crop plants

Nutrient	Biofertilizer type	Crop	Impact	Reference
Nitrogen	*Ustilago maydis* + *Bacillus pumilus*	–	Endosymbiotic N_2-fixing association	Ruiz-Herrera et al. (2015)
	Burkholderia ambifaria Mex-5	Grain amaranth (*Amaranthus*)	Promote grain yield	Parra-Cota et al. (2014)
	S. paucimobilis ZJSH1	Dendrobium (*D. officinale*)	Improve N fixation	Yang et al. (2014)
	Paenibacillus polymyxa P2b-2R	Red cedar (*Juniperus virginiana*)	Promote N fixation	Anand and Chanway (2013)
	Paenibacillus polymyxa P2b-2R	Lodgepole pine (*Pinus contorta*)	Enhances the growth of pine seedlings	Anand et al. (2013)
	RILs 34/104+ *Rhizobium tropici* CIAT899	Common bean (*Phaseolus vulgaris*)	Improve N fixation	Tajini and Drevon (2014)
	Bacterium BJ-18T	Wheat (*Triticum aestivum*)	Can improve N fixation	Wang et al. (2013a, b)
	BNF	Green foxtail (*Setaria viridis*)	Enhance growth	Pankievicz et al. (2015)
	Paenibacillus polymyxa ANM59	Chickpea (*Cicer arietinum*)	Improve growth of crop and soil fertility	Ahmad et al. (2019)
	R. huautlense	Dwarf willow (*Salix herbacea*)	Form nodules in flooded and non-flooded soils	Wang and Martinez-Romero (2000)
Phosphorus	*Paenibacillus* sp. ANM76	Chickpea (*Cicer arietinum*)	Improve P solubilization	Ahmad et al. (2019)
	Phosphate-solubilizing bacteria + organic acids	Rice (*Orzya sativa*)	Enhance P solubilization	Panhwar et al. (2013)
	Phytate mineralizing bacteria (PMB)	Common bean (*Phaseolus vulgaris*)	Increase P availability	Maougal et al. (2014)
	Phosphate-solubilizing bacterial (Ps-5, Ss-2)	Sunflower (*Helianthus annuus*)	Strong positive relation b/w phosphate solubilization and organic acid production	Shahid et al. (2015)
	Bacillus circulans (CB7)	Tomato (*Lycopersicon esculentum*)	Positive response for seed germination, plant	Mehta et al. (2015)

(continued)

Table 7.3 (continued)

Nutrient	Biofertilizer type	Crop	Impact	Reference
			growth and P solubilization	
	A. chroococum + *A. brasilense* + 30 kg ha^{-1}	Rice (*Orzya sativa*)	Improve growth and yield	Yadav et al. (2014)
	Pseudomonas fluorescens (DR54)	Maize (*Zea mays*)	Enhance P soluble soil pools at the early growth stage	Krey et al. (2013)
	Arsenic-resistance bacteria (*P. vittata*)	Tomato (*Solanum lycopersicum*)	Improve plant growth and nutrition	Ghosh et al. (2015)
	Burkholderia sp. (MTCC 8369) and *Gluconacetobacter* sp. (MTCC 8368)	Rice (*Orzya sativa*)	Improve P uptake, growth and yield	Stephen et al. (2015)
	RILs 34/104+ *Rhizobium tropici* CIAT899	Common bean (*Phaseolus vulgaris*)	Improve P utilization efficiency	Tajini and Drevon (2014)
Potassium	Potassium solubilizing bacteria (XF11) + k-feldspar powder	Tobacco (*Nicotiana tabacum*)	Increase in K and N uptake by tobacco seedlings	Zhang and Kong (2014)
	P-solubilizing (*Bacillus circulans* CB7)	Tomato (*Solanum lycopersicum*)	Improve plant growth and K solubilization	Mehta et al. (2015)

7.7 Conclusions

Nitrogen (N) and phosphorus (P) are the most important plant macronutrient, and their management is necessary for sustainable agriculture. Managing N and P in agroecosystem via smart use, limiting their losses and increasing use efficiency are major pillars and very much needed in modern-day agriculture practices. Nitrogen reserve in the atmosphere, though enormous, but require extensive utilization of fossil fuel for its conversion to plant usable form. Biological nitrogen fixation can be an alternative good option to opt. For P conservation, smart use of rock phosphate must be adopted to increase the life of remaining reserves. Involvement of precision agriculture, smart fertilizer modulation and minimizing fertilizer loss can be a major contributor to efficient N and P use in agriculture.

7.8 Future Perspectives

Although, plenty of work has been done for increasing the efficiency and reducing loses of nitrogen (N) and phosphorus (P) fertilizers in modern agricultural systems and practices but still there is huge gap to improve. New methods of availing N and P to plants can be found in which fewer natural resources are used. Integrated approaches may be used to enhance nitrogen and phosphorus use efficiency, i.e. good agricultural practices, 4R fertilizer placement, site specific application of fertilizers, use of innovative fertilizers, organic fertilization and improving the soil health and fertility status. Use of soil and atmospheric biota for providing N and P to plants can be a good option but proper understanding of mechanism and adoption for meeting the crop requirement is still needed. Soil fixed P can be converted to plant usable forms by the means of chemical as well as biological approaches. As P stocks of natural resources are very limited in the world and vanishing rapidly so there is a need to enhance the fertilizer use efficiency and reducing its loses in agro-ecosystem. P solubilizing microbes can be proved helpful for converting soil fixed P into labile pools but extensive screening and selection of microbes is required for this purpose. Climate smart fertilizers and slow-release fertilizers are good approaches to enhance the fertilizer use efficiency and reducing the fertilizer loses up to a certain range but a room is present in this field to further enhance the efficacy of these products.

References

Abbasi MK, Mansha S, Rahim N, Ali A (2013) Agronomic effectiveness and phosphorus utilization efficiency of rock phosphate applied to winter wheat. Agron J 105:1606–1612

Abbasi MK, Musa N, Manzoor M (2015) Mineralization of soluble P fertilizers and insoluble rock phosphate in response to phosphate-solubilizing bacteria and poultry manure and their effect on the growth and P utilization efficiency of chilli (*Capsicum annuum* L.). Biogeosciences 12:4607–4619

Ahmad M, Naseer I, Hussain A, Zahid Mumtaz M, Mustafa A, Hilger TH, Minggang X (2019) Appraising endophyte–plant symbiosis for improved growth, nodulation, nitrogen fixation and abiotic stress tolerance: An experimental investigation with chickpea (*Cicer arietinum* L.). Agronomy 9:621

Akiyama H, Uchida Y, Tago K, Hoshino YT, Shimomura Y, Wang Y, Hayatsu M (2015) Effect of dicyandiamide and polymer coated urea applications on N_2O, NO and CH_4 fluxes from Andosol and Fluvisol fields. Soil Sci Plant Nutr 61(3):541–551

Akkal-Corfini N, Morvan T, Menasseri-Aubry S, Bissuel-Bélaygue C, Poulain D, Orsini F, Leterme P (2010) Nitrogen mineralization, plant uptake and nitrate leaching following the incorporation of (^{15}N)-labeled cauliflower crop residues (*Brassica oleracea*) into the soil: A 3-year lysimeter study. Plant Soil 328:17–26

Alam SM, Shah SA, Akhter M (2003) Varietal differences in wheat yield and phosphorus use efficiency as influenced by method of phosphorus application. Songklanakarin J Sci Technol 25 (2):175–181

Alam SS, Moslehuddin AZM, Islam MR, Kamal AM (2010) Soil and foliar application of nitrogen for Boro rice (BRRIdhan 29). J Bangl Agric Univ 8(2):199–202

Al-Gaadi KA, Madugundu R, Tola E (2019) Investigating the response of soil and vegetable crops to poultry and cow manure using ground and satellite data. Saudi J Biol Sci 26(7):1392–1399

Ali M, Randhawa M, Ghafoor A, Ali L, Yamin M (2004) Effect of phosphorus application methods on yield of wheat. Pak J Life Soc Sci 11:1103–1110

Ali H, Sarwar N, Ahmad S, Tariq AW, Shahzad AN (2012) Response of wheat crop to phosphorus fertilizers and application methods grown under agro-climatic conditions of southern Punjab. Pak J Agric Sci 49:485–489

Ali MA, Naveed M, Mustafa A, Abbas A (2017) The good, the bad and the ugly of rhizosphere microbiome. In: Probiotics and plant health. Springer, Singapore, pp 253–290

Ali W, Ali M, Kamal A, Uzair M, Ullah N (2019) Maize yield response under various phosphorus sources and their ratios. Eur J Exp Biol 9(1):5

Álvarez CR, Álvarez R, Sarquis A (2008) Residue decomposition and fate of nitrogen-15 in a wheat crop under different previous crops and tillage systems. Commun Soil Sci Plant 39:574–586

Anand R, Chanway C (2013) N_2-fixation and growth promotion in cedar colonized by an endophytic strain of *Paenibacillus polymyxa*. Biol Fertil Soils 49:235–239

Anand R, Grayston S, Chanway C (2013) N_2-fixation and seedling growth promotion of lodgepole pine by endophytic *Paenibacillus polymyxa*. Microb Ecol 66:369–374

Anstoetz M, Rose TJ, Clark MW, Yee LH, Raymond CA, Vancov T (2015) Novel applications for oxalate-phosphate-amine metal-organic-frameworks (OPA-MOFs): can an iron-based OPA-MOF be used as slow-release fertilizer? PLoS One 10:e0144169

Arif M, Amin I, Jan MT, Munir I, Nawab K, Khan NU, Marwat KB (2010) Effect of plant population and nitrogen levels and methods of application on ear characters and yield of maize. Pak J Bot 42(3):1959–1967

Arora NK, Tewari S, Singh R (2013) Multifaceted plant-associated microbes and their mechanisms diminish the concept of direct and indirect PGPRs. In: Plant microbe symbiosis: fundamentals and advances. Springer, New Delhi, pp 411–449

Ashraf MN, Aziz T, Maqsood MA, Bilal HM, Raza S, Zia M, Mustafa A, Xu M, Wang Y (2019) Evaluating organic materials coating on urea as potential nitrification inhibitors for enhanced nitrogen recovery and growth of maize (*Zea mays*). Int J Agric Biol 22:1102–1108

Badr MA, Hussein SD, El-Tohamy WA (2015) Methods of phosphorus application and fertigation rate on eggplant yield and phosphorus use efficiency in sandy soil. Middle East J Appl Sci 5 (4):1055–1060

Bakhtiari MR (2014) Selection of fertilization method and fertilizer application rate on corn yield. Agric Eng Int CIGR J 16:10–14

Banerjee S, Palit R, Sengupta C, Standing D (2010) Stress induced phosphate solubilization by Arthrobacter sp. and Bacillus sp. isolated from tomato hizosphere. Aust J Crop Sci 4:378

Bardi L, Malusà E (2012) Drought and nutritional stresses in plant: alleviating role of rhizospheric microorganisms. In: Abiotic stress: new research. Nova Science Publishers Inc, Hauppauge, pp 1–57

Barker DW, Sawyer JE (2005) Nitrogen application to soybean at early reproductive development. Agron J 97(2):615–619

Bashan Y, Levanony H (1990) Current status of azospirillum inoculation technology: Azospirillum as a challenge for agriculture. Can J Microbiol 36:591–608

Bedmar EJ, Robles EF, Delgado MJ (2005) The complete denitrification pathway of the symbiotic, nitrogen-fixing bacterium Bradyrhizobium japonicum. Biochem Soc Trans 33(1):141–144

Behera SN, Sharma M, Aneja V, Balasubramanian R (2013) Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. Environ Sci Pollut Res 20:8092–8131

Belete F, Dechassa N, Molla A, Tana T (2018a) Effect of nitrogen fertilizer rates on grain yield and nitrogen uptake and use efficiency of bread wheat (*Triticum aestivum* L.) varieties on the Vertisols of central highlands of Ethiopia. Agric Food Secur 7:78

Belete F, Dechassa N, Molla A, Tana T (2018b) Effect of split application of different N rates on productivity and nitrogen use efficiency of bread wheat (*Triticum aestivum* L.). Agric Food Sec 7(1):92

Berruti A, Lumini E, Balestrini R, Bianciotto V (2016) Arbuscular mycorrhizal fungi as natural biofertilizers: let's benefit from past successes. Front Microbiol 6:1559

Bhattacharyya PN, Jha DK (2012) Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol 28:1327–1350

Black AS, Sherlock RR, Smith NP, Cameron KC, Goh KM (1985) Effects of form of nitrogen, season, and urea application rate on ammonia volatilisation from pastures. N Z J Agric Res 28:469–474

Bohlool BB, Ladha JK, Garrity DP, George T (1992) Biological nitrogen fixation for sustainable agriculture: a perspective. Plant Soil 141:1–11

Bortoletto-Santos R, Guimarães GGF, Roncato Junior V, Cruz DFD, Polito WL, Ribeiro C (2020) Biodegradable oil-based polymeric coatings on urea fertilizer: N release kinetic transformations of urea in soil. Sci Agric 77:1

Bosch-Serra ÀD, Yagüe MR, Teira-Esmatges MR (2014) Ammonia emissions from different fertilizing strategies in Mediterranean rainfed winter cereals. Atmos Environ 84:204–212

Brady NC, Weil RR (1999) Soil organic matter. The nature and properties of soils. Prentice Hall, Upper Saddle River, pp 446–490

Brock EH, Ketterings QM, Kleinman PJ (2007) Measuring and predicting the phosphorus sorption capacity of manure-amended soils. Soil Sci 172(4):266–278

Bücking H, Kafle A (2015) Role of arbuscular mycorrhizal fungi in the nitrogen uptake of plants: current knowledge and research gaps. Agronomy 5(4):587–612

Burgess MS, Mehuys R, Madramootoo CA (2002) Nitrogen dynamics of decomposing corn residue components under three tillage systems. Soil Sci Soc Am J 66:1350–1358

Calabi-Floody M, Medina J, Rumpel C, Condron LM, Hernandez M, Dumont M, de la Luz MM (2018) Smart fertilizers as a strategy for sustainable agriculture. Adv Agron 147:119–157

Cantarella H, Otto R, Soares JR, de Brito Silva AG (2018) Agronomic efficiency of NBPT as a urease inhibitor: a review. J Adv Res 13:19–27

Ch'ng HY, Ahmed OH, Majid NMA (2014) Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. Sci World J 2014:1–6

Chamani HE, Yasari E, Pirdashti H (2015) Response of yield and yield components of rice (*Oryza sativa* L. cv. Shiroodi) to different phosphate solubilizing microorganisms and mineral phosphorous. Int J Biol Sci 6:70–75

Charpentier M, Oldroyd G (2010) How close are we to nitrogen-fixing cereals? Curr Opin Plant Biol 13:556–564

Chaturvedi I (2005) Effect of nitrogen fertilizers on growth, yield and quality of hybrid rice (*Oryza sativa*). J Cent Eur Agric 6:611–618

Chen D, Suter H, Islam A, Edis R, Freney JR, Walker CR (2008) Prospects of improving efficiency of fertilizer nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. Aust J Soil Res 46:289–301

Chen XP, Cui ZL, Vitousek PM, Cassman KG, Matson P, Bai JS, Zhang FS (2011) Integrated soil–crop system management for food security. Proc Natl Acad Sci U S A 108:6399–6404

Chen X, Cui Z, Fan M, Vitousek P, Zhao Ma W, Deng X (2014) Producing more grain with lower environmental costs. Nature 514:486

Chen Z, Wang H, Liu X, Liu Y, Gao S, Zhou J (2016) The effect of N fertilizer placement on the fate of urea-15N and yield of winter wheat in southeast China. PLoS One 11:e0153701

Cherr CM, Scholberg JMS, McSorley R (2006) Green manure approaches to crop production. Agron J 98:302–319

Chien SH, Prochnow LI, Cantarella AH (2009) Recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts. Adv Agron 102:267–322

Chien SH, Prochnow LI, Tu S, Snyder CS (2011) Agronomic and environmental aspects of phosphate fertilizers varying in source and solubility: an update review. Nutr Cycl Agroecosyst 89:229–255

Chien SH, Sikora FJ, Gilkes RJ, McLaughlin MJ (2012) Comparing of the difference and balance methods to calculate percent recovery of fertilizer phosphorus applied to soils: a critical discussion. Nutr Cycl Agroecosyst 92:1–8

Ciampitti IA, Vyn TJ (2013) Grain nitrogen source changes over time in maize: a review. Crop Sci 53:366–377

Cordell D, Drangert JO, White S (2009) The story of phosphorus: global food security and food for thought. Glob Environ Chang 19:292–305

Criquet S, Braud A, Nèble S (2007) Short-term effects of sewage sludge application on phosphatase activities and available P fractions in Mediterranean soils. Soil Biol Biochem 39:921–929

Cui Z, Zhang F, Chen X, Dou Z, Li J (2010) In-season nitrogen management strategy for winter wheat: maximizing yields, minimizing environmental impact in an over-fertilization context. Field Crop Res 116:140–146

Cui HJ, Wang MK, Ci FML (2011) Enhancing phosphorus availability in phosphorus-fertilized zones by reducing phosphate adsorbed on ferrihydrite using rice straw-derived biochar. J Soils Sediments 11:1135

da Silva Mazareli RC, Duda RM, Leite VD, de Oliveira RA (2016) Anaerobic co-digestion of vegetable waste and swine wastewater in high-rate horizontal reactors with fixed bed. Waste Manag 52:112–121

Damon PM, Bowden B, Rose T, Rengel Z (2014) Crop residue contributions to phosphorus pools in agricultural soils: a review. Soil Biol Biochem 74:127–137

Danso EO, Abenney-Mickson S, Sabi EB, Plauborg F, Abekoe M, Kugblenu YO, Andersen MN (2015) Effect of different fertilization and irrigation methods on nitrogen uptake, intercepted radiation and yield of okra (*Abelmoschus esculentum* L.) grown in the Keta Sand Spit of Southeast Ghana. Agric Water Manag 147:34–42

Darch T, Blackwell MS, Hawkins JMB, Haygarth PM, Chadwick D (2014) A meta-analysis of organic and inorganic phosphorus in organic fertilizers, soils, and water: Implications for water quality. Crit Rev Environ Sci Technol 44:2172–2202

Darzi MT (2012) Effects of organic manure and biofertilizer application on flowering and some yield traits of coriander (*Coriandrum sativum*). Int J Agric Crop Sci 43:103–107

Davidson EA (2009) The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. Nat Geosci 2:659–662

de Castro RC, de Melo BV, Teixeira PC, dos Anjos MJ, de Oliveira LF (2015) Phosphorus migration analysis using synchrotron radiation in soil treated with Brazilian granular fertilizers. Appl Radiat Isot 105:233–237

de Figueiredo CC, Barbosa DV, de Oliveira SA, Fagioli M, Sato JH (2012) Polymer-coated phosphate fertilizer and liming on the production and morphological parameters of corn. Rev Ciênc Agron 43:446

Dikgwatlhe SB, Chen ZD, Lal R, Zhang H, Chen F (2014) Changes in soil organic carbon and nitrogen as affected by tillage and residue management under wheat–maize cropping system in the North China Plain. Soil Tillage Res 144:110–118

Dixon R, Kahn D (2004) Genetic regulation of biological nitrogen fixation. Nat Rev Microbiol 2 (8):621–631

Dominghetti AW, Guelfi DR, Guimarães RJ, Caputo ALC, Spehar CR, Faquin V (2016) Nitrogen loss by volatilization of nitrogen fertilizers applied to coffee orchard. Ciên Agrotechnol 40:173–183

Douxchamps S, Frossard E, Bernasconi SM, Van der Hoek R, Schmidt A, Rao IM, Oberson A (2011) Nitrogen recoveries from organic amendments in crop and soil assessed by isotope techniques under tropical field conditions. Plant Soil 341:179–192

Duarte LO, Aquino LAD, Caixeta IAB, Gonçalves FAR, Reis MRD (2019) Rates and methods of phosphorus application in cabbage crop. Pesqui Agropecu Trop 49:e54191

El-Eyuoon A, Amin AZ (2018) Improvement in phosphorus use efficiency of corn crop by amending the soil with sulfur and farmyard manure. Soil Environ 37(1):62–67

Endris S (2019) Combined application of phosphorus fertilizer with tithonia biomass improves grain yield and agronomic phosphorus use efficiency of hybrid maize. Int J Agron 2019:1–9

Fageria NK (2002) Influence of micronutrients on dry matter yield and interaction with other nutrients in annual crops. Pesqui Agropecu Bras 37:1765–1772

Fageria NK, Baligar VC (2005) Enhancing nitrogen use efficiency in crop plants. Adv Agron 88:97–185

Fan XH, Li YC (2010) Nitrogen release from slow-release fertilizers as affected by soil type and temperature. Soil Sci Soc Am J 74:1635

Fan X, Li F, Liu F, Kumar D (2004) Fertilization with a new type of coated urea: evaluation for nitrogen efficiency and yield in winter wheat. J Plant Nutr 27:853–865

FAO (2018) Agriculture Organization of the United Nations (2013) Food outlook: biannual report on global food markets

Farrar K, Bryant D, Cope Selby N (2014) Understanding and engineering beneficial plant–microbe interactions: plant growth promotion in energy crops. Plant Biotechnol J 12:1193–1206

Faucon MP, Houben D, Reynoird JP, Mercadal-Dulaurent AM, Armand R, Lambers H (2015) Advances and perspectives to improve the phosphorus availability in cropping systems for agroecological phosphorus management. Adv Agron 134:51–79

Ferrol N, Azcón-Aguilar C, Pérez-Tienda J (2019) Review: arbuscular mycorrhizas as key players in sustainable plant phosphorus acquisition: an overview on the mechanisms involved. Plant Sci 280:441–447

Fleet ME, Liu X, Liu X (2011) Orientation of channel carbonate ions in apatite: Effect of pressure and composition. Am Mineral 96:1148–1157

Fließbach A, Oberholzer HR, Gunst L, Mäder P (2007) Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agric Ecosyst Environ 118:273–284

Follmer C (2008) Insights into the role and structure of plant ureases. Phytochemistry 69:18–28

Fowler CJE, Condron LM, McLenaghen RD (2004) Effects of green manures on nitrogen loss and availability in an organic cropping system. N Z J Agric Res 47:95–100

Frame W (2017) Ammonia volatilization from urea treated with NBPT and two nitrification inhibitors. Agron J 109:378–387

Frossard E, Sinaj S, Zhang LM, Morel JL (1996) The fate of sludge phosphorus in soil-plant systems. Soil Sci Soc Am J 60:1248

Gagnon B, Ziadi N, Grant C (2012) Urea fertilizer forms affect grain corn yield and nitrogen use efficiency. Can J Soil Sci 92:341–351

Galloway JN, Dentener FJ, Capone DG, Boyer EW, Howarth RW, Seitzinger SP, Asner GP, Cleveland CC, Green PA, Holland EA, Karl DM, Michaels AF, Porter JH, Townsend AR, Vorsmarty CJ (2004) Nitrogen cycles, past, present, and future. Biogeochemistry 70:153–226

Galloway JN, Leach AM, Bleeker A, Erisman JW (2013) A chronology of human understanding of the nitrogen cycle. Philos Trans R Soc B Biol Sci 368:120

Gerke J (1992) Orthophosphate and organic phosphate in the soil solution of four sandy soils in relation to pH: evidence for humic-Fe (Al) phosphate complexes. Commun Soil Sci Plant Anal 23:601–612

Ghaly AE, Ramakrishnan VV (2015) Nitrogen sources and cycling in the ecosystem and its role in air, water and soil pollution: a critical review. J Pollut Effects Cont 3(2):1–26

Ghoneim AM, Gewaily EE, Osman MM (2018) Effects of nitrogen levels on growth, yield and nitrogen use efficiency of some newly released Egyptian rice genotypes. Open Agric 3:310–318

Ghosh P, Rathinasabapathi B, Ma LQ (2015) Phosphorus solubilization and plant growth enhancement by arsenic-resistant bacteria. Chemosphere 134:1–6

Giroto AS, Guimarães GG, Foschini M, Ribeiro C (2017) Role of slow-release nanocomposite fertilizers on nitrogen and phosphate availability in soil. Sci Rep 7:46032

Glaser B, Wiedner K, Seelig S, Schmidt HP, Gerber H (2015) Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. Agron Sustain Dev 35(2):667–678

Glass ADM (2003) Nitrogen use efficiency of crop plants: Physiological constraints upon nitrogen absorption. CRC Crit Rev Plant Sci 22:453–470

Guan Y, Song C, Gan Y, Li FM (2014) Increased maize yield using slow-release attapulgite-coated fertilizers. Agron Sustain Dev 34:657–665

Guiñazú LB, Andrés JA, Del Papa MF, Pistorio M, Rosas SB (2009) Response of alfalfa (*Medicago sativa* L.) to single and mixed inoculation with phosphate-solubilizing bacteria and *Sinorhizobium meliloti*. Biol Fertil Soils 46:185–190

Guo R, Li X, Christie P, Chen Q, Jiang R, Zhang F (2008) Influence of root zone nitrogen management and a summer catch crop on cucumber yield and soil mineral nitrogen dynamics in intensive production systems. Plant Soil 313:55–70

Guppy CN, Menzies NW, Moody PW, Blamey FPC (2005) Competitive sorption reactions between phosphorus and organic matter in soil: a review. Soil Res 43:189–202

Halvorson AD, Snyder CS, Blaylock AD, Del Grosso SJ (2014) Enhanced-efficiency nitrogen fertilizers: potential role in nitrous oxide emission mitigation. Agron J 106:715–722

Hammond JP, Broadley MR, White PJ, King GJ, Bowen HC, Hayden R, Greenwood DJ (2009) Shoot yield drives phosphorus use efficiency in *Brassica oleracea* and correlates with root architecture traits. J Exp Bot 60:1953–1968

Hardy RW (1993) Biological nitrogen fertilization: present and future applications. In: Agriculture and environmental challenges. Proc 13th Agric. Sector Symp. The World Bank, Washington, DC, pp 109–117

Hasan MM, Hasan MM, da Silva JAT, Li X (2016) Regulation of phosphorus uptake and utilization: transitioning from current knowledge to practical strategies. Cell Mol Biol Lett 21:7

He CE, Wang X, Liu X, Fangmeier A, Christie P, Zhang F (2010) Nitrogen deposition and its contribution to nutrient inputs to intensively managed agricultural ecosystems. Ecol Appl 20:80–90

He Y, Yang S, Xu J, Wang Y, Peng S (2014) Ammonia volatilization losses from paddy fields under controlled irrigation with different drainage treatments. Sci World J 2014:1–7

Herridge DF, Peoples MB, Boddey RM (2008) Global inputs of biological nitrogen fixation in agricultural systems. Plant Soil 311:1–18

Hirel B, Le Gouis J, Ne B, Gallais A (2007) The challenge of improving nitrogen use efficiency in crop plants: towards a more central role for genetic variability and quantitative genetics within integrated approaches. J Exp Bot 58:2369–2387

Holcomb JC, Sullivan DM, Horneck DA, Clough GH (2011) Effect of irrigation rate on ammonia volatilization. Soil Sci Soc Am J 75:2341–2347

Hongshao Z, Stanforth R (2001) Competitive adsorption of phosphate and arsenate on goethite. Environ Sci Technol 35:4753–4757

Horrocks A, Curtin D, Tregurtha C, Meenken E (2016) Municipal compost as a nutrient source for organic crop production in New Zealand. Agronomy 6(2):35

Hu F (2016) The effect of fertilizer placement of the growth of rice and wheat and fertilizer use efficiency. PhD dissertation. Inst. Soil Sci. Chinese Acad. Sci., China

Hu G, Liu X, He H, Zhang W, Xie H, Wu Y, Zhang X (2015) Multi-seasonal nitrogen recoveries from crop residue in soil and crop in a temperate agro-ecosystem. PLoS One 10(7):e0133437

Imran M, Irfan M, Yaseen M, Rasheed N (2018) Application of glycerin and polymer coated diammonium phosphate in alkaline calcareous soil for improving wheat growth, grain yield and phosphorus use efficiency. J Crop Sci Biotechnol 21:425–434

Iqbal Z, Yaqub M, Akram MZ, Ahmad R (2013) Phosphorus fertigation: a technique for enhancing P fertilizer efficiency and yield of wheat and maize. Soil Environ 32(2):146–151

Islam MA, Adjesiwor AT (2017) Nitrogen fixation and transfer in agricultural production systems. In: Nitrogen in agriculture-updates. IntechOpen, London

Islam MS, Paul NK, Alam MR, Uddin MR, Sarker UK, Islam MA, Park SU (2015) Responses of rice to green manure and nitrogen fertilizer application. Online J Biol Sci 15:207

Jadon P, Selladurai R, Yadav SS, Coumar MV, Dotaniya ML, Singh AK, Kundu S (2018) Volatilization and leaching losses of nitrogen from different coated urea fertilizers. J Soil Sci Plant Nutr 18(4):1036–1047

Jangir CK, Singh D, Kumar S (2016) Yield and economic response of biofertilizer and fertility levels on black gram (*Vigna mungo* L.). Progr Res 11:5252–5254

Jensen ES, Bedoussac L, Carlsson G, Journet EP, Justes E, Hauggaard-Nielsen H (2015) Mint: enhancing yields in organic crop production by eco-functional intensification. Sustain Agric Res 4:42–50

Jetiyanon K (2015) Multiple mechanisms of *Enterobacter asburiaestrain* RS83 for plant growth enhancement. Songklanakarin J Sci Technol 37:29–36

Jiang CQ, Lu D, Wang S, Zhou J, Zu C, Wang H (2017) Research on placement site of urea single application in summer maize. J Agric Sci Technol 19:67–74

Jiang C, Lu D, Zu C, Shen J, Wang S, Guo Z, Wang H (2018) One-time root-zone N fertilization increases maize yield, NUE and reduces soil N losses in lime concretion black soil. Sci Rep 8:10258

Jury WA, Nielsen DR (1989) Nitrate transport and leaching mechanisms. Dev Agric Manage Forest Ecol 21:139–157

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in Indo-Gangatic Plains of India. J Curr Microbiol Appl Sci 6(3):152–163

Kakraliya SK, Singh U, Bohra A, Choudhary KK, Kumar S, Meena RS, Jat ML (2018) Nitrogen and legumes: a meta-analysis. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, New York, pp 277–314. https://doi.org/10.1007/978-981-13-0253-4_9

Kamran S, Shahid I, Baig DN, Rizwan M, Malik KA, Mehnaz S (2017) Contribution of zinc solubilizing bacteria in growth promotion and zinc content of wheat. Front Microbiol 8:2593

Kanwar JS, Grewal JS (1990) Phosphorus fixation in Indian soils: a review. Publications and Information Division Indian Council of Agricultural Research Krishi Anusandhan Bhavan, Pusa, New Delhi

Kauwenbergh SJV, Hellums DT (1995) Direct application phosphate rock: a contemporary snap-shot. In: Phosphorus and potassium-including statistical supplement of the British Sulphur Corp., pp 27–37

Kennedy IR, Choudhury ATMA, Kecskes ML (2004) Non-symbiotic bacterial diazotrophs in crop-farming systems: can their potential for plant growth promotion be better exploited? Soil Biol Biochem 36:1229–1244

Kesler SE, Simon AC, Simon AF (2015) Mineral resources, economics and the environment. Cambridge University Press, Cambridge

Kettering J, Ruidisch M, Gaviria C, Ok YS, Kuzyakov Y (2013) Fate of fertilizer 15N in intensive ridge cultivation with plastic mulching under a monsoon climate. Nutr Cycl Agroecosyst 95:57–72

Khalid A, Arshad M, Shaharoona B, Mahmood T (2009) Plant growth promoting rhizobacteria and sustainable agriculture. In: Microbial strategies for crop improvement. Springer, Berlin, pp 133–160

Khan R, Gurmani AR, Gurmani AH, Zia MS (2007) Effect of phosphorus application on wheat and rice yield under wheat-rice system. Sarhad J Agric 23:851

Khan QU, Khan MJ, Ullah S (2010) Comparison of different models for phosphate adsorption in salt inherent soil series of Dera Ismail Khan. Soil Environ 29:11–14

Khan MMA, Haque E, Paul NC, Khaleque MA, Al-Garni SMS, Rahman M, Islam MT (2017) Enhancement of growth and grain yield of rice in nutrient deficient soils by rice probiotic bacteria. Rice Sci 24:264–273

Killham K (2011) Integrated soil management–moving towards globally sustainable agriculture. J Agric Sci 149(S1):29–36

Kim J, Rees DC (1994) Nitrogenase and biological nitrogen fixation. Biochemistry 33:389–397

Kim JG, Kim JH, Moon H, Chon C, Ahn JS (2002) Removal capacity of water plant alum sludge for phosphorus in aqueous solution. Chem Spec Bioavailab 14:67–73

Kizito S, Luo H, Lu J, Bah H, Dong R, Wu S (2019) Role of nutrient-enriched biochar as a soil amendment during maize growth: exploring practical alternatives to recycle agricultural residuals and to reduce chemical fertilizer demand. Sustain For 11:3211

Kloepper JW, Scher FM, Tripping B (1986) Emergence promoting rhizobacteria: description and implication for agriculture. In: Swinburne TR (ed) Iron, siderophores and plant diseases. Plenum, New York, pp 155–164

Korzeniowska J, Stanisławska-Glubiak E, Hoffmann J, Górecka H, Jóźwiak W, Wiśniewska G (2013) Improvement of the solubility of rock phosphate by co-composting it with organic components. Pol J Chem Technol 15:10–14

Krey T, Baum C, Ruppel S, Seydel M, Eichler-Löbermann B (2013) Organic and inorganic P sources interacting with applied rhizosphere bacteria and their effects on growth and P supply of maize. Commun Soil Sci Plant Anal 44:3205–3215

Kudashev IS (1956) The effect of phospho-bacterin on the yield and protein content in grains of autumm wheat, maize, and soybean. Doki Akad Skh Nauk 8:20–23

Kumar A, Maurya BR, Raghuwanshi R (2014) Isolation and characterization of PGPR and their effect on growth, yield and nutrient content in wheat (*Triticum aestivum* L.). Biocatal Agric Biotechnol 3:121–128

Kumar S, Meena RS, Lal R (2018) Role of legumes in soil carbon sequestration. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, New York, pp 109–138. https://doi.org/10.1007/978-981-13-0253-4_4

Kumari B, Mallick MA, Solanki MK, Solanki AC, Hora A, Guo W (2019) Plant growth promoting rhizobacteria (PGPR): modern prospects for sustainable agriculture. In: Plant Health Under Biotic Stress. Springer, Singapore, pp 109–127

Kumawat N, Kumar R, Sharma OP (2009) Nutrient uptake and yield of mungbean [*Vigna radiate* (L.) Wilczek] as influenced by organic manures, PSB and phosphorus fertilization. Environ Ecol 27(4B):2002–2005

Kumawat K, Patel PP, Dambiwal D, Reddy TV, Hakla CR (2017) Effect of liquid and solid bio-fertilizers (Rhizobium and PSB) on growth attributes, yield and economics of fenugreek (*Trigonella foenum-graecum* L). IJCS 5:239–242

Laboski CA, Lamb JA (2003) Changes in soil test phosphorus concentration after application of manure or fertilizer. Soil Sci Soc Am J 67:544–554

Lam SK, Suter H, Mosier AR, Chen D (2017) Using nitrification inhibitors to mitigate agricultural N_2O emission: a double-edged sword? Glob Chang Biol 23:485–489

Lan ZM, Lin XJ, Wang F, Zhang H, Chen CR (2012) Phosphorus availability and rice grain yield in a paddy soil in response to long-term fertilization. Biol Fertil Soils 48(5):579–588

Lassaletta L, Billen G, Grizzetti B, Anglade J, Garnier J (2014) 50-year trends in nitrogen use Lehmann J & Joseph S (Eds.), Biochar for environmental management: science, technology and implementation. Routledge, Abingdon

Layek J, Das A, Mitran T, Nath C, Meena RS, Yadav GS, Shivakumar BG, Kumar S, Lal R (2018) Cereal+legume intercropping: an option for improving productivity and sustaining soil health. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, New York, pp 347–386. https://doi.org/10.1007/978-981-13-0253-4_11

Lehmann J, Joseph S (eds) (2015) Biochar for environmental management: science, technology and implementation. Routledge, Abingdon

Li Y, Ren B, Ding L, Shen Q, Peng S, Guo S (2013) Does chloroplast size influence photosynthetic nitrogen use efficiency? PLoS One 8:e62036

Li S, Li J, Lu J, Wang Z (2015) Effect of mixed urease inhibitors on N losses from surface-applied urea. Int J Agric Sci Technol 3:23–27

Li Q, Cui X, Liu X, Roelcke M, Pasda G, Zerulla W (2017) A new urease-inhibiting formulation decreases ammonia volatilization and improves maize nitrogen utilization in North China Plain. Sci Rep 7:43853

Li Q, Xu C, Yin C, Kong L, Qin Y, Hou Y, Wang H, Zhao L (2019) Evaluation of fertigation technique for phosphorus application of maize in the semi-arid region of Northeast China. Plant Soil Environ 65(8):401–407

Liu Y, Chen J (2008) Phosphorus cycle. Encycl Ecol 2008:2715–2724

Liu Y, Wu L, Baddeley JA, Watson CA (2011) Models of biological nitrogen fixation of legumes. Sust Agric 2:883–905

Liu C, Lu M, Cui J, Li B, Fang CM (2014) Effects of straw carbon input on carbon dynamics in agricultural soils: a meta–analysis. Glob Chang Biol 20:1366–1381

Liu X, Wang H, Zhou J, Hu F, Zhu D, Chen Z, Liu Y (2016) Effect of N fertilization pattern on rice yield, N use efficiency and fertilizer–N fate in the Yangtze River Basin, China. PLoS One 11: e0166002

Liu J, Yang J, Cade-Menun BJ, Hu Y, Li J, Peng C, Ma Y (2017) Molecular speciation and transformation of soil legacy phosphorus with and without long-term phosphorus fertilization: Insights from bulk and microprobe spectroscopy. Sci Rep 7:15354

Lu D, Song H, Jiang S, Chen X, Wang H, Zhou J (2018) Integrated phosphorus placement and form for improving wheat grain yield. Agron J 111(4):1998–2004

Luo G, Li L, Friman VP, Guo J, Guo S, Shen Q, Ling N (2018) Organic amendments increase crop yields by improving microbe-mediated soil functioning of agroecosystems: a meta-analysis. Soil Biol Biochem 124:105–115

Luxhoi J, Elsgaard L, Thomsen IK, Jensen LS (2007) Effects of long-term annual inputs of straw and organic manure on plant N uptake and soil N fluxes. Soil Use Manag 23:368–373

Lwin C, Maung K, Murakami M, Hashimoto S (2017) Scenarios of phosphorus flow from agriculture and domestic wastewater in Myanmar (2010–2100). Sustain For 9:1377

Ma Q, Rengel Z, Rose T (2009) The effectiveness of deep placement of fertilizers is determined by crop species and edaphic conditions in Mediterranean-type environments: a review. Soil Res 47:19–32

Mabrouk Y, Hemissi I, Salem IB, Mejr S, Saidi M, Belhadj O (2018) Potential of rhizobia in improving nitrogen fixation and yields of legumes. In: Symbiosis. InTech Open, London, p 107

Mackenzie FT (1998) Our changing planet. An introduction to earth system science and global environmental change, 2nd edn. Prentice Hall, Upper Saddle River

Mäder P, Fliessbach A, Dubois GL, Fried P, Niggli U (2002) Soil fertility and biodiversity in organic farming. Science 296:1694–1697

Malusá E, Vassilev N (2014) A contribution to set a legal framework for biofertilisers. Microb Biotechnol 98:6599–6607

Maougal RT, Brauman A, Plassar C, Abadie J, Djekoun A, Drevon JJ (2014) Bacterial capacities to mineralize phytate increase in the rhizosphere of nodulated common bean (*Phaseolus vulgaris*) under P deficiency. Eur J Soil Biol 62:8–14

Massawe PI, Mrema J (2017) Effects of different phosphorus fertilizers on rice (*Oryza sativa* L.) yield components and grain yields. Asian J Adv Agric Res 13:1527

Masunga RH, Uzokwe VN, Mlay PD, Odeh I, Singh A, Buchan D, De Neve S (2016) Nitrogen mineralization dynamics of different valuable organic amendments commonly used in agriculture. Appl Soil Ecol 101:185–193

Mazid M, Khan TA (2015) Future of bio-fertilizers in Indian agriculture: an overview. Int J Agric Food Res 3(3):10–23

McLaughlin MJ, McBeath TM, Smernik R, Stacey SP, Ajiboye B, Guppy C (2011) The chemical nature of P accumulation in agricultural soils implications for fertiliser management and design: an Australian perspective. Plant Soil 349:69–87

Meena H, Meena RS, Rajput BS, Kumar S (2016) Response of bio-regulators to morphology and yield of cluster bean [*Cyamopsis tetragonoloba* (L.) Taub.] under different sowing environments. J Appl Nat Sci 8(2):715–718

Meena RS, Kumar V, Yadav GS, Mitran T (2018) Response and interaction of *Bradyrhizobium japonicum* and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Lal R, Yadav GS (2020) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Mehta P, Walia A, Kulshrestha S, Chauhan A, Shirkot CK (2015) Efficiency of plant growth-promoting P-solubilizing *Bacillus circulans* CB7 for enhancement of tomato growth under net house conditions. J Basic Microbiol 55:33–44

Meisinger JJ, Delgado JA (2002) Principles for managing nitrogen leaching. J Soil Water Conserv 57:485–498

Minet E, Coxon CE, Goodhue R, Richards KG, Kalin RM, Meier-Augenstein W (2012) Evaluating the utility of 15N and 18O isotope abundance analyses to identify nitrate sources: a soil zone study. Water Res 46:3723–3736

Mira AB, Cantarella H, Souza-Nettoa GJM, Moreira LA, Kamogawa MY, Otto R (2017) Optimizing urease inhibitor usage to reduce ammonia emission following urea application over crop residues. Agric Ecosyst Environ 248:105–112

Misselbrook TH, Cardenas LM, Camp V, Thorman RE, Williams JR, Rollett AJ, Chambers BJ (2014) An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. Environ Res Lett 9:115006

Mitran T, Meena RS, Lal R, Layek J, Kumar S, Meena BL, Datta R (2018) Role of soil phosphorus on legume production. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, New York, pp 487–510. https://doi.org/10.1007/978-981-13-0253-4_15

Modolo LV, Souza AX, Horta LP, Araujo DP, Fátima A (2015) An overview on the potential of natural products as ureases inhibitors. J Adv Res 6:35–44

Mohanty SK, Singh U, Balasubramanian V, Jha KP (1998) Nitrogen deep-placement technologies for productivity, profitability, and environmental quality of rainfed lowland rice systems. Nutr Cycl Agroecosyst 53:43–57

Mosali J (2004) Effect of foliar application of phosphorus on winter wheat grain yield, and use of in-season reflectance for predicting yield potential in bermudagrass (Doctoral dissertation, Oklahoma State University)

Mosberger L, Lazzaro A (2008) Ecology and diversity of diazotrophs in the environment. Term paper in biogeochemistry and pollutant dynamics. Swiss Federal Institute of Technology Zurich

Mosier A, Bleken M, Chaiwanakupt P, Elllis EC, Freney JR, Howrath RB, Matson PA, Minami K, Naylor R, Weeks KN, Zhu ZL (2001) Policy implications of human-accelerated nitrogen cycling. Biogeochemistry 52:281–320

Munson RD, Murphy LS (1986) Factors affecting crop response to phosphorus. Phosphorus for agriculture, a situation analysis. Potash and Phosphate Institute, Atlanta, pp 9–24

Mustafa A, Naveed M, Saeed Q, Ashraf MN, Hussain A, Abbas T, Kamran M, Minggang X (2019) Application potentials of plant growth promoting rhizobacteria and fungi as an alternative to conventional weed control methods. In: Crop production. IntechOpen, London

Nadeem SM, Ahmad M, Zahir ZA, Javaid A, Ashraf M (2014) The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. Biotechnol Adv 32:429–448

Najm AA, Hadi MRHS, Fazeli F, Darzi MT, Rahi A (2012) Effect of integrated management of nitrogen fertilizer and cattle manure on the leaf chlorophyll, yield, and tuber glycoalkaloids of Agria potato. Commun Soil Sci Plant 43:912–923

Nardi P, Neri U, Di Matteo G, Trinchera A, Napoli R, Farina R, Subbarao GV, Benedetti A (2018) Nitrogen release from slow-release fertilizers in soils with different microbial activities. Pedosphere 28:332–340

Naseer I, Ahmad M, Nadeem SM, Ahmad I, Zahir ZA (2019) Rhizobial inoculants for sustainable agriculture: prospects and applications. In: Biofertilizers for sustainable agriculture and environment. Springer, Cham, pp 245–283

Nash PR, Nelson KA, Motavalli PP (2013) Corn yield response to timing of strip-tillage and nitrogen source applications. Agron J 105:623–630

Näsholm T, Kielland K, Ganeteg U (2009) Uptake of organic nitrogen by plants. New Phytol 182 (1):31–48

Neff JC, Townsend AR, Gleixner G, Lehman SJ, Turnbull J, Bowman WD (2002) Variable effects of nitrogen additions on the stability and turnover of soil carbon. Nature 419:915

Ni K, Pacholski A, Kage H (2014) Ammonia volatilization after application of urea to winter wheat over 3 years affected by novel urease and nitrification inhibitors. Agric Ecosyst Environ 197:184–194

Niamat B, Naveed M, Ahmad Z, Yaseen M, Ditta A, Mustafa A, Rafique M, Bibi R, Sun N, Xu M (2019) Calcium-enriched animal manure alleviates the adverse effects of salt stress on growth, physiology and nutrients homeostasis of *Zea mays* L. Plants 8:480

Nin Y, Diao P, Wang Q, Zhang Q, Zhao Z, Li Z (2016) On-farm-produced organic amendments on maintaining and enhancing soil fertility and nitrogen availability in organic or low input agriculture. Organ Fert 2016:289–307

Nobile C, Houben D, Michel E, Firmin S, Lambers H, Kandeler E, Faucon MP (2019) Phosphorus-acquisition strategies of canola, wheat and barley in soil amended with sewage sludges. Sci Rep 9(1):1–11

Noellsch AJ, Motavalli PP, Nelson KA, Kitchen NR (2009) Corn response to conventional and slow-release nitrogen fertilizers across a claypan landscape. Agron J 101:607

Noonari S, Kalhoro SA, Ali A, Mahar A, Raza S, Ahmed M, Baloch SU (2016) Effect of different levels of phosphorus and method of application on the growth and yield of wheat. Nat Sci 8:305

Noor MA, Nawaz MM, Hassan M, Sher A, Shah T, Abrar MM, Ashraf U, Fiaz S, Basahi MA, Ahmed W, Ma W (2020) Small farmers and sustainable N and P management: Implications and potential under changing climate. In: Carbon and nitrogen cycling in soil. Springer, Singapore, pp 185–219

Oenema O, van Liere L, Schoumans O (2005) Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in the Netherlands. J Hydrol 304:289–301

Okito A, Alves BRJ, Urquiaga S, Boddey RM (2004) Isotopic fractionation during N_2 fixation by four tropical legumes. Soil Biol Biochem 36(7):1179–1190

Ott C, Rechberger H (2012) The European phosphorus balance. Resour Conserv Recycl 60:159–172

Pagliari PH, Laboski CA (2012) Investigation of the inorganic and organic phosphorus forms in animal manure. J Environ Qual 41(3):901–910

Pan B, Lam SK, Mosier A, Luo Y, Chen D (2016) Ammonia volatilization from synthetic fertilizers and its mitigation strategies: a global synthesis. Agric Ecosyst Environ 232:283–289

Panhwar QA, Jusop S, Naher UA, Othman R, Razi MI (2013) Application of potential phosphate-solubilizing bacteria and organic acids on phosphate solubilization from phosphate rock in aerobic rice. Sci World J 2013:272409

Pankievicz VC, do Amaral FP, Santos KF, Agtuca B, Xu Y, Schueller MJ (2015) Robust biological nitrogen fixation in a model grass–bacterial association. Plant J 81:907–919

Parmar N, Dadarwal KR (1999) Stimulation of nitrogen fixation and induction of flavonoid like compounds by rhizobacteria. J Appl Microbiol 86:36–44

Parra-Cota F, Peña-Cabriales JJ, de los Santos-Villalobos S, Martínez-Gallardo NA, Délano-Frier JP (2014) *Burkholderia ambifaria* and *B. caribensis* promote growth and increase yield in grain amaranth (*Amaranthus cruentus* and *A. hypochondriacus*) by improving plant nitrogen uptake. PLoS One 9(2):e88094

Peix A, Ramírez-Bahena MH, Velázquez E, Bedmar EJ (2015) Bacterial associations with legumes. Crit Rev Plant Sci 34:17–42

Picazevicz AAC, Kusdra JF, Moreno ADL (2017) Maize growth in response to *Azospirillum brasilense*, *Rhizobium tropici*, molybdenum and nitrogen. Rev Bras Eng Agric Ambient 21:623–627

Pitta CSR, Adami PF, Pelissari A, Assmann TS, Franchin MF, Cassol LC, Sartor LR (2012) Year-round poultry litter decomposition and N, P, K and Ca release. Rev Bras Ciênc Solo 36:1043–1053

Placido J, Capareda S, Karthikeyan R (2016) Production of humic substances from cotton stalks biochar by fungal treatment with *Ceriporiopsis subvermispora*. Sustain Energy Technol Assess 13:31–37

Poblete-Grant P, Biron P, Bariac T, Cartes P, Mora MDLL, Rumpel C (2019) Synergistic and antagonistic effects of poultry manure and phosphate rock on soil P availability, ryegrass production, and P uptake. Agronomy 9(4):191

Pokhrel BB, Sah SK, Amgain LP, Ojha BR (2009) Response of promising maize cultivars to different nitrogen levels in winter. In: Proceeding of the tenth Asian regional maize workshop, pp 479–483

Postgate J (1998) Nitrogen fixation, 3rd edn. Cambridge University Press, Cambridge

Power JF, Doran JW, Wilhelm WW (1986) Mint: uptake of nitrogen from soil, fertilizer, crop residues by no-till corn and soybeans. Soil Sci Soc Am J 50:137–142

Rafiullah KMJ, Muhammad D (2017) Foliar application of phosphorus to enhance phosphorus utilization and crop growth: a hydroponic study. Sarhad J Agric 34:47–53

Rahim A, Abbassi GH, Rashid M, Ranjha AM (2007) Methods of phosphorus application and irrigation schedule influencing wheat yield. Pak J Agric Sci 44(3):420–423

Rahim A, Ranjha AM, Waraich EA (2010) Effect of phosphorus application and irrigation scheduling on wheat yield and phosphorus use efficiency. Soil Environ 29:15–22

Randall GW, Vetch JA (2003) Corn production on a subsurface-drain Mollisol as affected by time of nitrogen application and nitrapyrin. Agron J 95:1213–1219

Rani K, Sharma P, Kumar S, Wati L, Kumar R, Gurjar DS, Kumar D, Kumar R (2019) Legumes for sustainable soil and crop management. In: Meena RS, Kumar S, Bohra JS, Jat ML (eds) Sustainable management of soil and environment. Springer, New York, pp 193–215. https://doi.org/10.1007/978-981-13-8832-3_6

Rascio N, La Rocca N (2008) Biological nitrogen fixation. Ency Ecol 2008:412–419

Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F, Crutzen PJ (2012) Global agriculture and nitrous oxide emissions. Nat Clim Chang 2(6):410–416

Redding MR, Lewis R, Kearton T, Smith O (2016) Manure and sorbent fertilisers increase on-going nutrient availability relative to conventional fertilisers. Sci Total Environ 569:927–936

Ren B, Zhan J, Dong S, Liu P, Zhao B, Li H (2017) Nitrapyrin improves grain yield and nitrogen use efficiency of summer maize waterlogged in the field. Agron J 109:185–192

Roberts TL, Johnston AE (2015) Phosphorus use efficiency and management in agriculture. Resour Conserv Recycl 105:275–281

Robertson GP, Groffman PM (2007) Nitrogen transformations. In: Soil microbiology, ecology and biochemistry. Academic, Cambridge, pp 341–364

Robertson GP, Groffman PM (2009) Nitrogen in agriculture: balancing the cost of an essential resource. Annu Rev Environ Resour 34:97–125

Rosling A, Midgley MG, Cheeke T, Urbina H, Fransson P, Phillips RP (2016) Phosphorus cycling in deciduous forest soil differs between stands dominated by ecto-and arbuscular mycorrhizal trees. New Phytol 209:1184–1195

Rubin RL, van Groenigen KJ, Hungate BA (2017) Plant growth promoting rhizobacteria are more effective under drought: a meta-analysis. Plant Soil 416(1-2):309–323

Ruiz-Herrera J, León-Ramírez C, Vera-Nuñez A, Sánchez-Arreguín A, Ruiz-Medrano R, Salgado-Lugo H, Peña-Cabriales JJ (2015) A novel intracellular nitrogen-fixing symbiosis made by *Ustilago* maydis and *Bacillus* spp. New Phytol 207:769–777

Rybárová Z, Slamka P, Ložek O, Kováčik P (2018) Effectiveness of the application of nitrification inhibitors on the content of available nitrogen forms in the soil after winter barley cultivation. Agriculture 64:95–105

Saeed Z, Naveed M, Imran M, Bashir MA, Sattar A, Mustafa A, Hussain A, Xu M (2019) Combined use of Enterobacter sp. MN17 and zeolite reverts the adverse effects of cadmium on growth, physiology and antioxidant activity of *Brassica napus*. PLoS One 14:e0213016

Samreen T, Zahir ZA, Naveed M, Asghar M (2019) Boron tolerant phosphorus solubilizing *Bacillus* spp. MN-54 improved canola growth in alkaline calcareous soils. Int J Agric Biol 21:538–546

Santos SRD, Lustosa Filho JF, Vergütz L, Melo LCA (2019) Biochar association with phosphate fertilizer and its influence on phosphorus use efficiency by maize. Cien Agrotechnol 43:e025718

Schilling G, Gransee A, Deuhel A, Ležoviž G, Ruppel S (1998) Phosphorus availability, root exudates, and microbial activity in the rhizosphere. Zeitschrift für Pflanzenernährung und Bodenkd 161:465–478

Schlögl R (2008) Ammonia synthesis. In: Handbook of heterogeneous catalysis, 2nd edn. Springer, New York, pp 2501–2575

Scholz RW, Wellmer FW (2013) Approaching a dynamic view on the availability of mineral resources: what we may learn from the case of phosphorus? Glob Environ Chang 23:11–27

Shahid M, Hameed S, Tariq M, Zafar M, Ali A, Ahmad N (2015) Characterization of mineral phosphate-solubilizing bacteria for enhanced sunflower growth and yield-attributing traits. Ann Microbiol 65:1525–1536

Shakoor A, Ashraf M, Shah L, Ali A, Khan A, Sher A (2015) Impact of farmyard manure and nitrogen, phosphorus, and potassium on maize crop. Acad Res J Agric Sci Res 3:219–223

Sharpley A, Robinson JS, Smith SJ (1995) Assessing environmental sustainability of agricultural systems by simulation of nitrogen and phosphorus loss in runoff. Eur J Agron 4:453–464

Shivay YS, Pooniya V, Prasad R, Pal M, Bansal R (2016) Sulphur-coated urea as a source of sulphur and an enhanced efficiency of nitrogen fertilizer for spring wheat. Cereal Res Commun 44:513–523

Shrestha J (2015) Growth and productivity of winter maize (*Zea mays* L.) under different levels of nitrogen and plant population. Universal-Publishers, Irvine

Shrestha J, Chaudhary A, Pokhrel D (2018) Application of nitrogen fertilizer in maize in Southern Asia: a review. Peruv J Agron 2:22–26

Smil V (1999) Nitrogen in crop production: an account of global flows. Global Biogeochem Cycles 13:647–662

Smil V (2000) Phosphorus in the environment: natural flows and human interferences. Annu Rev Energy Environ 25:53–88

Smil V (2004) Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production. MIT Press, Cambridge

Song K, Xue Y, Zheng X, Lv W, Qiao H, Qin Q, Yang J (2017) Effects of the continuous use of organic manure and chemical fertilizer on soil inorganic phosphorus fractions in calcareous soil. Sci Rep 7(1):1–19

Stauffer E, Andrade FV, de Sa ME, Donagemma GK (2019) Enhanced efficiency phosphate fertilizers and phosphorus availability in Acrudox. Aust J Crop Sci 13:61

Stephen J, Shabanamol S, Rishad KS, Jisha MS (2015) Growth enhancement of rice (*Oryza sativa*) by phosphate solubilizing *Gluconacetobacter* sp. (MTCC 8368) and *Burkholderia* sp. (MTCC 8369) under greenhouse conditions. Biotech 5:831–837

Stevens WB, Blaylock AD, Krall JM, Hopkins BG, Ellsworth JW (2007) Sugarbeet yield and nitrogen use efficiency with preplant broadcast, banded, or point-injected nitrogen application. Agron J 99(5):1252–1259

Stevenson FJ, Cole MA (1999) Cycles of soils: carbon, nitrogen, phosphorus, sulfur, micronutrients. Wiley, Hoboken

Stumm W (1977) Global chemical cycles and their alterations by man. Abakon Verlagsgesellschaft, Berlin

Syers JK, Johnston A, Curtin D (2008) Efficiency of soil and fertilizer phosphorus use. FAO Fert Plant Nutr Bull 18:108

Tajini F, Drevon JJ (2014) Phosphorus use efficiency for symbiotic nitrogen fixation varies among common bean recombinant inbred lines under P deficiency. J Plant Nutr 37(4):532–545

Talboys PJ, Heppell J, Roose T, Healey JR, Jones DL, Withers PJ (2016) Struvite: a slow-release fertiliser for sustainable phosphorus management. Plant Soil 401(1-2):109–123

Tariq N, Ali H, Ahmad S, Rasheed M, Chattha TH, Hussain A (2012) Growth and radiation use efficiency of wheat as affected by different irrigation levels and phosphorus application methods. J Anim Plant Sci 22:1118–1125

Teixeira RDS, Ribeiro da Silva I, Nogueira de Sousa R, Márcio Mattiello E, Barros Soares EM (2016) Organic acid coated-slow-release phosphorus fertilizers improve P availability and maize growth in a tropical soil. J Soil Sci Plant Nutr 16(4):1097–1112

Tian C, Zhou X, Liu Q, Peng JW, Wang WM, Zhang ZH, Guan CY (2016) Effects of a controlled-release fertilizer on yield, nutrient uptake, and fertilizer usage efficiency in early ripening rapeseed (*Brassica napus* L.). J Zhejiang Univ Sci B 17(10):775–786

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418(6898):671–677

Tomar NK (2003) Effect of soil properties on the kinetics of P description on acid soils. J Indian Soc Soil Sci 51:508–511

Tong X, He X, Duan H, Han L, Huang G (2018) Evaluation of controlled release urea on the dynamics of nitrate, ammonium, and its nitrogen release in black soils of northeast China. Int J Environ Res Publ 15:119

Toor GS, Hunger S, Peak JD, Sims JT, Sparks DL (2006) Advances in the characterization of phosphorus in organic wastes: environmental and agronomic applications. Adv Agron 89:1–72

Trenkel ME (2010) Slow-and controlled-release and stabilized fertilizers: an option for enhancing nutrient use efficiency in agriculture. IFA, Int. Fertilizer Indus. Assoc

Turner DA, Edis RE, Chen D, Freney JR, Denmead OT (2012) Ammonia volatilization from nitrogen fertilizers applied to cereals in two cropping areas of southern Australia. Nutr Cycl Agroecosyst 93:113–126

Ullah I, Ali N, Durrani S, Shabaz MA, Hafeez A, Ameer H, Waheed A (2018) Effect of different nitrogen levels on growth, yield and yield contributing attributes of wheat. Int J Sci Eng Res 9:595–602

Unkovich M, Herridge D, Peoples M, Cadisch G, Boddey B, Giller K, Van Kauwenbergh SJ (2010) World phosphate rock reserves and resources. IFDC, Muscle Shoals, p 48

Van Kauwenbergh SJ (1995) Mineralogy and characterization of phosphate rock. In: Direct application of phosphate rock and appropriate technology fertilizers in Asia-what hinders accep. and growth, pp 29–47

Vance CP (1998) Legume symbiotic nitrogen fixation: agronomic aspects. In the rhiz

Vance CP, Uhde-Stone C, Allan DL (2003) Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. New Phytol 157:423–447

Varadachari C, Goertz HM (2010) Slow-release and controlled-release nitrogen fertilizers. Ind. N Group, Soc

Varley JB, Wang Y, Chan K, Studt F, Nørskov JK (2015) Mechanistic insights into nitrogen fixation by nitrogenase enzymes. Phys Chem Chem Phys 17(44):29541–29547

Vassileva M, Azcon R, Barea JM, Vasslev N (2000) Rock phosphate solubilization by free and encapsulated cells of Yarowia lipolytica. Process Biochem 35:693–697

Verzeaux J, Hirel B, Dubois F, Lea PJ, Tétu T (2017) Agricultural practices to improve nitrogen use efficiency through the use of arbuscular mycorrhizae: basic and agronomic aspects. Plant Sci 264:48–56

Vidal EA, Moyano TC, Canales J, Gutiérrez RA (2014) Nitrogen control of developmental phase transitions in Arabidopsis thaliana. J Exp Bot 65(19):5611–5618

Vitousek PM, Menge DN, Reed SC (1621) Cleveland CC (2013) Biological nitrogen fixation: rates, patterns and ecological controls in terrestrial ecosystems. Philos T Roy Soc B 368:20130119

Vojvodic A, Medford AJ, Studt F, Abild-Pedersen F, Khan TS, Bligaard T, Nørskov JK (2014) Exploring the limits: a low-pressure, low-temperature Haber–Bosch process. Chem Phys Lett 598:108–112

Waldrip HM, He Z, Erich MS (2011) Effects of poultry manure amendment on phosphorus uptake by ryegrass, soil phosphorus fractions and phosphatase activity. Biol Fertil Soils 47(4):407–418

Wang ET, Martinez-Romero E (2000) Sesbania herbacea–Rhizobium huautlense nodulation in flooded soils and comparative characterization of S. herbacea-nodulating Rhizobia in different environments. Microb Ecol 40(1):25–32

Wang LY, Li J, Li QX, Chen SF (2013a) *Paenibacillus beijingensis* sp. nov., a nitrogen-fixing species isolated from wheat rhizosphere soil. Van Leeuw 104(5):675–683

Wang X, Liu F, Tan W, Li W, Feng X, Sparks DL (2013b) Characteristics of phosphate adsorption-desorption onto ferrihydrite: Comparison with well-crystalline Fe (hydr) oxides. Soil Sci 178 (1):1–11

Wang C, Wang X, Liu D, Wu H, Lü X, Fang Y, Yin H (2014) Aridity threshold in controlling ecosystem nitrogen cycling in arid and semi-arid grasslands. Nat Commun 5:4799

Wang S, Zhao X, Xing G, Yang Y, Zhang M, Chen H (2015) Improving grain yield and reducing N loss using polymer-coated urea in southeast China. Agron Sustain Dev 35(3):1103–1115

Wang S, Luo S, Yue S, Shen Y, Li S (2016) Fate of 15N fertilizer under different nitrogen split applications to plastic mulched maize in semiarid farmland. Nutr Cycl Agroecosyst 105:129–140

Waqar A, Hira K, Ullah B, Khan A, Shah Z, Khan FA, Naz RMM (2014) Role of nitrogen fertilizer in crop productivity and environmental pollution. Int J Agric Forest 4(3):201–206

Whalen JK, Sampedro L (2010) Soil ecology and management. CABI, Wallingford

Whelan A, Kechavarzi C, Coulon F, Sakrabani R, Lord R (2013a) Influence of compost amendments on the hydraulic functioning of brownfield soils. Soil Use Manag 29(2):260–270

Whelan ME, Min DH, Rhew RC (2013b) Salt marshes as a source of atmospheric carbonyl sulfide. Atmos Environ 73:131–137

Wu M, Li G, Li W, Liu J, Liu M, Jiang C, Li Z (2017) Nitrogen fertilizer deep placement for increased grain yield and nitrogen recovery efficiency in rice grown in subtropical China. Front Plant Sci 8:1227

Xiang YAN, Jin JY, Ping HE, Liang MZ (2008) Recent advances on the technologies to increase fertilizer use efficiency. Agric Sci China 7(4):469–479

Xiang J, Haden VR, Peng S, Bouman BA, Huang J, Cui K, Chen H (2013) Effect of deep placement of nitrogen fertilizer on growth, yield, and nitrogen uptake of aerobic rice. Aust J Crop Sci 7 (6):870

Xiang Y, Ru X, Shi J, Song J, Zhao H, Liu Y, Zhao G (2018) Granular, slow-release fertilizer from urea-formaldehyde, ammonium polyphosphate, and amorphous silica gel: a new strategy using cold extrusion. J Agric Food Chem 66(29):7606–7615

Xie C, Tang J, Zhao J, Wu D, Xu X (2011a) Comparison of phosphorus fractions and alkaline phosphatase activity in sludge, soils, and sediments. J Soils Sediments 11(8):1432–1439

Xie L, Liu M, Ni B, Zhang X, Wang Y (2011b) Slow-release nitrogen and boron fertilizer from a functional superabsorbent formulation based on wheat straw and attapulgite. Chem Eng J 167 (1):342–348

Xu G, Fan X, Miller AJ (2012) Plant nitrogen assimilation and use efficiency. Annu Rev Plant Biol 63:153–182

Yadav J, Verma JP, Jaiswal DK, Kumar A (2014) Evaluation of PGPR and different concentration of phosphorus level on plant growth, yield and nutrient content of rice (*Oryza sativa*). Ecol Eng 62:123–128

Yamamoto CF, Pereira EI, Mattoso LH, Matsunaka T, Ribeiro C (2016) Slow release fertilizers based on urea/urea–formaldehyde polymer nanocomposites. Chem Eng J 287:390–397

Yang X, Wu X, Hao HL, He ZL (2008) Mechanisms and assessment of water eutrophication. J Zhejiang Univ Sci B 9(3):197–209

Yang J, Cheng W, Lin H, Liu X, Hu Y (2010) Effect of palygorskite adding NPK fertilizer on plant dry matter accumulation and polysaccharide content of Radix Hedysari. Med Plant 1(4):1–7

Yang Y, He Z, Yang X, Fan J, Stoffella P, Brittain C (2012) Dolomite phosphate rock–based slow-release fertilizer for agriculture and landscapes. Commun Soil Sci Plant 43(9):1344–1362

Yang S, Zhang X, Cao Z, Zhao K, Wang S, Chen M, Hu X (2014) Growth-promoting S phingomonas paucimobilis ZJSH 1 associated with D endrobium officinale through phytohormone production and nitrogen fixation. Microb Biotechnol 7(6):611–620

Yao Y, Zhang M, Tian Y, Zhao M, Zhang B, Zhao M, Yin B (2018) Urea deep placement for minimizing NH3 loss in an intensive rice cropping system. Field Crop Res 218:254–266

Yeshiwas Y, Zewdie BYB, Chekol A, Walle A (2018) Effect of nitrogen fertilizer and farmyard manure on growth and yield of lettuce (*Lactuca sativa* L.). Agribiol Res 13(2):74–79

Yong TW, Ping C, Qian D, Qing D, Feng Y, Wang XC, Yang WY (2018) Optimized nitrogen application methods to improve nitrogen use efficiency and nodule nitrogen fixation in a maize-soybean relay intercropping system. J Integr Agric 17(3):664–676

Zahir ZA, Arshad M, Frankenberger WT (2004) Plant growth promoting rhizobacteria: applications and perspectives in agriculture. Adv Agron 81:96–168

Zahran HH (2001) Rhizobia from wild legumes: diversity, taxonomy, ecology, nitrogen fixation and biotechnology. J Biotechnol 91:143–153

Zaman M, Blennerhassett JD (2010) Effects of the different rates of urease and nitrification inhibitors on gaseous emissions of ammonia and nitrous oxide, nitrate leaching and pasture production from urine patches in an intensive grazed pasture system. Agric Ecosyst Environ 136:236–246

Zaman M, Saggar S, Stafford AD (2013) Mitigation of ammonia losses from urea applied to a pastoral system: the effect of BTPT and timing and amount of irrigation. NZ. Grassland Assoc 75:121–126

Zenawi G, Mizan A (2019) Effect of nitrogen fertilization on the growth and seed yield of sesame (Sesamum indicum L.). Int J Agro. https://doi.org/10.1155/2019/5027254

Zhang C, Kong F (2014) Isolation and identification of potassium-solubilizing bacteria from tobacco rhizospheric soil and their effect on tobacco plants. Appl Soil Ecol 82:18–25

Zhang M, Wang H, Yi Y, Ding J, Zhu M, Li C, Zhu X (2017) Effect of nitrogen levels and nitrogen ratios on lodging resistance and yield potential of winter wheat (*Triticum aestivum* L.). PLoS One 12(11):e0187543

Zheng W, Liu Z, Zhang M, Shi Y, Zhu Q, Sun Y, Geng J (2017) Improving crop yields, nitrogen use efficiencies, and profits by using mixtures of coated controlled-released and n coated urea in a wheat-maize system. Field Crop Res 205:106–115

Zhu ZL, Chen DL (2002) Nitrogen fertilizer use in China-contributions to food production, impacts on the environment and best management strategies. Nutr Cycl Agroecosyst 63:117–127

Zhu X, Li C, Jiang Z, Huang L, Feng C, Guo W, Peng Y (2012) Responses of phosphorus use efficiency, grain yield, and quality to phosphorus application amount of weak-gluten wheat. J Integr Agric 11(7):1103–1110

Zhu L, Yang H, Zhao Y, Kang K, Liu Y, He P, Wei Z (2019) Biochar combined with montmorillonite amendments increase bioavailable organic nitrogen and reduce nitrogen loss during composting. Bioresour Technol 294:122224

Zou N, Dart PJ, Marcar NE (1995) Interaction of salinity and rhizobial strain on growth and N_2-fixation by Acacia ampliceps. Soil Biol Biochem 27(4-5):409–413

Long-Term Impact of Fertilizers on Soil and Rice Productivity

8

Md Mozammel Haque and Jatish C. Biswas

Contents

Abstract

Indigenous soil nutrients play a vital role in profitable crop production, but its capacity diminishes based on nutrient management options over the years. We assessed the long-term effects of fertilization on rice (*Oryza sativa* L.) grain yield and soil fertility status under rice-fallow-rice pattern based on original and reviewed data. The management strategies were omission of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), and zinc (Zn) fertilizers and reversing treatments for the recuperation of soil fertility were used after 15 years of experimentation and continued for 9 years. Unfertilized plot regained its productive potential of rice after 9 years through the use of balanced NPKSZn fertilizers. However, the only use of chemical fertilizers was not enough for sustained rice

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production under studied conditions. Although recuperation of soil fertility can be done by adopting different management options, the use of recommended chemical fertilizer dose in severely depleted soils was inadequate for improving K, S, and Zn status of the soil. Rice grain yields significantly increased (31–45%) under organic amendments than only chemical fertilizer treatment. So, organic and inorganic fertilizer management could be a good option for increasing soil organic carbon balance along with the fulfillment of food demand. It is hypothesized that soil fertility and crop productivity change with addition of similar types of fertilizers for a long time that warrants dose corrections periodically for sustainable food production.

Keywords

Long-term · Missing element · Rice-fallow-rice system · Fertility status

Abbreviations

BRRI	Bangladesh Rice Research Institute
C	Carbon
CD	Cow dung
CH_4	Methane
CO_2	Carbon dioxide
Eq	Equivalent
GHGs	Greenhouse gases
GWP	Global warming potential
ha	Hectare
K	Potassium
kg	Kilograms
N	Nitrogen
P	Phosphorus
PM	Poultry manure
ppm	Part per million
S	Sulphur
SOC	Soil organic carbon
SOM	Soil organic matter
Zn	Zinc

8.1 Introduction

Rice, a staple food for about 150 million peoples in Bangladesh, occupies 74.64% of the total cropped areas (BBS 2017). New rice genotypes and farming innovations have greatly augmented its production in Bangladesh from about 11 million tons in 1971–1972 to about 35 million tons in 2014–2015 (AIS 2016). This higher production was mostly because of greater adoption of new varieties (Kabir et al. 2015),

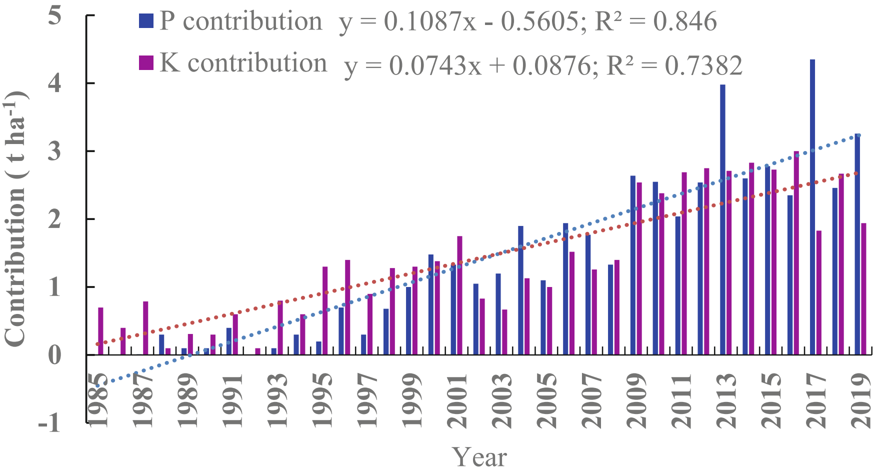


Fig. 8.1 Contributions of added P and K fertilizers to dry-season (Boro) irrigated rice yield at Bangladesh Rice Research Institute (BRRI), Gazipur (Data source: Haque et al. 2015c, 2017a, 2019a)

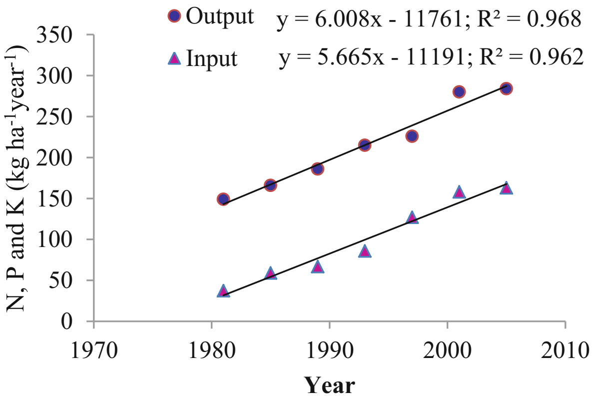


Fig. 8.2 Nitrogen, phosphorus, and potassium input-output scenarios for crop production in Bangladesh (Data source: Emran et al. 2019)

irrigation facility development, and use of nutrient elements such as nitrogen (N), phosphorus (P), and potassium (K) fertilizers (Figs. 8.1 and 8.2). However, rapid industrialization and other structural development are also making agricultural lands unproductive. Besides, Bangladesh suffers from drought, flooding, and cyclones, and the intensities of such disasters are increasing (ADRC 2018; Biswas et al. 2019a), and thus damages crops very severely in many instances. Under such situations and depending on crop season length, choice of variety and fertilizer management can alleviate yield reduction and thus total production (Sihag et al. 2015; Kumar et al. 2017; Meena et al. 2017).

Organic and inorganic nutrient sources and adoption of better agronomic management practices could be imperative for improving crop productivity, soil

Fig. 8.3 Boro rice yield as influenced by nitrogen rates (Adapted from booklet on Modern rice cultivation, BRRI, different editions)

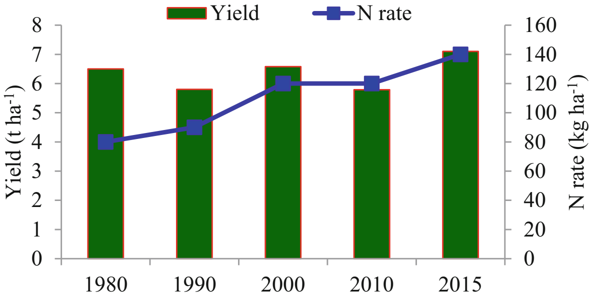
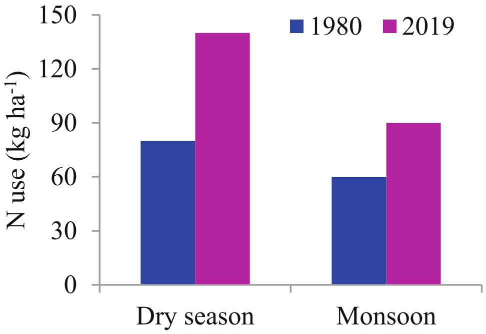


Fig. 8.4 Changes in nitrogen requirements for growing rice (Adapted from various issues of Annual Reports of BRRI)



properties, and net carbon (C) budget (Sihi et al. 2017; Bajiya et al. 2017; Varma et al. 2017; Haque et al. 2019a, c). Although large amounts of chemical fertilizers are used in Bangladesh, farmers generally use more urea fertilizer than others (Biswas et al. 2008). Continuous chemical and lack of balanced fertilization are considered to be the leading cause of rice yield stability or decline (Saleque et al. 2004; Haque et al. 2019a). Moreover, we need to add more N fertilizer to have almost similar rice yield at present compared to 1980 (Figs. 8.3 and 8.4). In 1980, about 80 kg N ha^{-1} (hectare) was needed for about 6.5-ton ha^{-1} grain yield of Boro rice, and now we have to add about 140 kg N ha^{-1}, an increase of about 75% in four decades to have similar yield. Many experiments are conducted on fertilizer management to provide preliminary fertilizer, but it needs further calibration and validation through multi-year trials and readjustments based on cropping sequences and time.

Generally, observed rice productivity trends are declining in many long-term fertilization trials under different rice cropping patterns (Yadvinder et al. 2005; Haque et al. 2015c, 2019a). Since rice-fallow-rice is the most dominant cropping pattern in Bangladesh and covers about 27% of the cropland (Nasim et al. 2017), we hypothesize that long-term fertilizer management with varied nutrient combinations influences soil health and rice productivity. Moreover, the reduction in grain yields was mostly related with gradual depletion in soil nutrients status, soil organic carbon (SOC) content, lack of better agronomic management practices, and changes in the biochemical and physical properties of SOC (Haque et al. 2015a; Jakhar et al. 2017; Kumar et al. 2018; Timsina et al. 2018; Meena et al. 2019; Kumar et al. 2020).

Table 8.1 Effect of cropping patterns on global warming potential (GWP) in Bangladesh with standard chemical fertilization

Cropping system	CH_4 emission (kg ha^{-1})	GWP (CO_2 eq. kg ha^{-1})
Jute-T. Aman-fallow	48	3129f
Boro (intermittent drainage)-T. Aman-fallow	196	7191b
Boro (continuous flooding)-T. Aman-fallow	295	9688a
Wheat-T. Aus-T. Aman	97	4592c
Maize-fallow-T. Aman	48	3988d
Potato-maize-T. Aman	48	4618c
Wheat-Mungbean-T. Aman	48	3315e

Small letters in a column compare mean at 5% level of probability by LSD
CO_2 carbon dioxide, *Eq*. equivalent, *kg* kilograms

Agricultural management practices such as green manuring, incorporation of cover crop biomass, use of poultry litter, mustard oil cake, vermicompost, etc. cannot only supply plant nutrients, but also affect soil organic matter (SOM) contents (Haque et al. 2015a, 2019a, c), aggregate stability (Haque et al. 2019b), water holding capacity (Zhang and Fang 2007), bulk density (Haque et al. 2015a), and ultimately grain yields (Timsina et al. 2018; Haque et al. 2019a). Although the addition of different organic materials into rice field can increase methane (CH_4) emission and global warming potential (GWP) (Haque et al. 2013, 2015d; Ibrahim et al. 2015), the total increase in global food production is feasible. It is necessary in assessing crop productivity and soil health for sustained food production and in formulating effective adaptation strategy for minimizing yield reduction and GWP (Haque et al. 2016, 2017b, c). For example, the selection of suitable cropping pattern, water management, and choice of crop varieties can reduce greenhouse gases (GHGs) emissions and GWP from crop fields (Table 8.1 and Fig. 8.5). Therefore, the objectives of the present studies were to find out the influence of missing elements on soil fertility and rice yield and to find out the ways of the rejuvenating capacity of soil through fertilizer management for sustained crop production in Bangladesh and similar environment around the globe.

8.2 Impact of Green Revolution on Rice Agroecosystem

Increased total crop production around the globe was the immediate effects of the green revolution, which was related to the use of improved varieties, fertilizers, and irrigation water. Although such practices are also responsible for increased emissions of GHGs such as CH_4 and nitrous oxide (N_2O), incorporation of decomposable organic materials into the soil system also improves crop productivity and soil net C budget. With such anthropogenic activities, the contribution of agriculture to global GHG emission is about 10–12%. Many strategies have been employed to

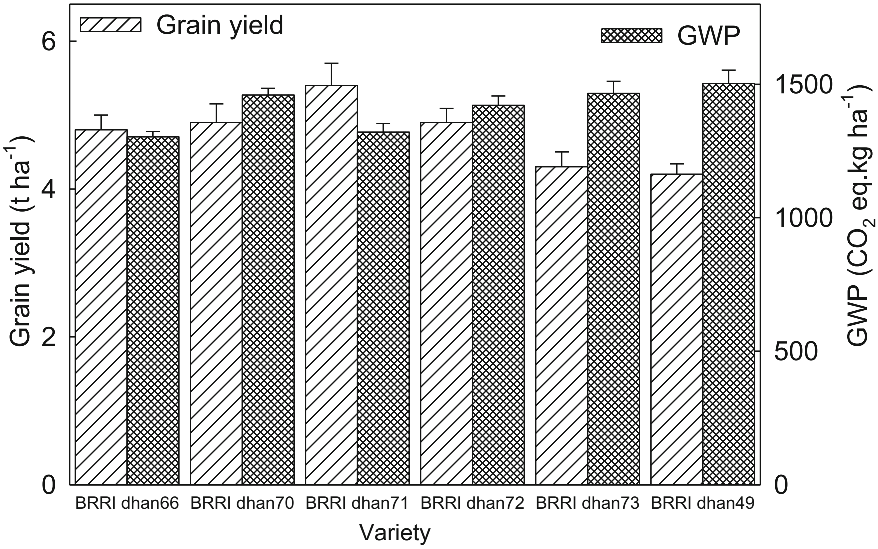


Fig. 8.5 Grain yield and GWP as of the influence of varietal characters

reduce CH_4 emission, such as the use of straw biochar, manipulating tillage operations, fertilizer and water management. On the other hand, some suitable rice cultivars gave higher yield but emit lesser amounts of GHG. So, selecting suitable rice cultivars could be one of the important management options for reducing GHGs and GWP and increased rice productivity.

8.3 Rice Yield Variations Under Different Fertilizer Management Options

The indigenous nutrient supply capacity of soils gradually depleted over times depending on adopted cropping pattern and fertilizer management options. It is necessary to know how long soil can provide nutrients for plants to grow satisfactorily. A trial was initiated on a stable layout at the BRRI farm, Gazipur in 1985 Boro season. In Boro 2000, each plot was subdivided to include a reverse treatment (addition of nutrient or nutrients to the missing plots) and to evaluate their effect on soil fertility and rice yield. Different fertilizer treatment combinations were evaluated (Table 8.2). In that trial, missing nutrients were replenished from fertilizers after 15 years following standard recommended practices for rice production and continued for nine years.

Complete chemical fertilizer treatment (NPKSZn; S—sulphur, Zn—zinc) gave significantly ($p < 0.05$) higher mean grain yield than all missing nutrients after 9 years (Tables 8.3 and 8.4). All reverse treatments showed significantly higher yield than original treatments except all missing nutrients. The novelty of this research is

Table 8.2 Treatments used in the long-term experiment, 1985–2008

Original treatment 1985	NPKSZn	PKSZn (–N)	NKSZn (–P)	NPSZn (–K)	NPKZn (–S)	NPKS (–Zn)	Control
Reverse treatment 2000–2008	All missing	PKSZn (+N)	NKSZn (+P)	NPSZn (+K)	NPKZn (+S)	NPKS (+Zn)	Reverse control

Adapted from Haque et al. (2015c, 2017a)

that no literature is available on change patterns of grain yields and soil nutrient status under reverse treatment conditions. Grain yield reduction due to N limitation was more prominent in PKSZn (–N) treatment ($p < 0.05$) than in PKSZn (+N). Mean grain yield was approximately 35% higher in PKSZn (+N) compare to PKSZn (–N) (Table 8.3).

Nitrogen is the most limiting nutrient element that hinders grain yield improvement of rice in Bangladesh along with other Asian countries (Ahmmed et al. 2018), P and K deficiencies also play a substantial role for higher grain yields. The deficiency of certain nutrient element or excess application of a particular element shifted nutrient ratios antagonistically, and thus influences crop yields (Biswas et al. 2017a, 2019c). Potassium mining is widespread in Bangladesh along with emerging new nutrient element deficiencies (Saha et al. 2016; Meena et al. 2016; Haque et al. 2019c) in many parts of the world that should be addressed for sustained production of rice and other principal food crops in Asian countries. Widespread nutrient mining is also taking place in other countries (Bhattacharyya et al. 2006; Lee et al. 2008) and thus hampering food production, especially in developing countries.

Added nutrients in soils behave differently depending on crop culture, properties of fertilizers, and resultant nutrient ratios. For example, the contribution of added P up to 10–12 years was not prominent with dry-season irrigated rice culture in Bangladesh and then improved gradually. In the wet season, the contribution of added P was negligible (Haque et al. 2019a). It was found that the addition of P fertilizer after 9 years gave 30% higher grain yield of rice than P omission plots. Continuous use of P at 50 kg ha^{-1} $year^{-1}$ resulted in soil P build-up of 21–30 parts per million (ppm) in 33 years (Haque et al. 2019a). Saleque et al. (2004) also reported P build-up depending on cropping patterns and status of indigenous soil fertility. However, if initial soil P is about 10 ppm, its dose can even be reduced up to 10–12 years, although it should be done based on soil–plant response study.

Although K fertilization during 2000–2008 significantly ($p < 0.05$ level) improved rice productivity, negative K balance is widespread in Bangladesh even with recommended K doses (Haque et al. 2019a). The mean grain yield with NPKSZn treatment after 9 years was around 24% higher than K missing treatment. Since soil K levels in major areas are very low to low (Biswas et al. 2019b), its mining is taking place in Bangladesh because farmers use minimum K fertilizer for crop production. However, mining of K is taking place in the paddy fields even with national standard K doses. Rice plants uptake inordinate amounts of K, but most of it remains in the straw (Swarup and Wanjari 2000; Haque et al. 2014, 2015c, 2019a).

Table 8.3 Yearly rice production with different nutrient combinations during 2000–2008

	Original treatment	Reverse treatment	Original treatment	Reverse treatment	Original treatment	Reverse treatment	Original treatment	Reverse treatment
Year	NPKSZn	All missing	–N	+N	–P	+P	–K	+K
2000	10.38	6.47	8.06	10.16	6.10	10.25	6.35	10.05
2001	9.47	7.10	8.89	10.22	7.00	9.84	7.22	9.55
2002	8.46	5.41	6.30	8.45	8.48	9.19	8.05	9.32
2003	7.25	4.83	5.84	8.45	7.17	8.33	6.86	8.06
2004	9.85	5.95	7.38	9.82	8.04	9.22	7.61	9.16
2005	9.80	5.90	7.37	9.93	7.18	9.62	8.48	9.26
2006	9.80	6.37	7.14	10.47	7.41	10.17	8.18	10.14
2007	10.43	5.89	6.90	10.28	7.32	9.80	8.31	9.63
2008	9.40	5.56	6.79	9.38	7.03	9.13	6.88	8.97
Mean	9.43	5.94	7.19	9.68	7.30	9.51	7.55	9.35
$LSD_{0.05}$	0.603	0.39	0.43	0.44	0.25	0.23	0.14	0.19

Table 8.4 Yearly grain yield with fertilized and unfertilized plots during 2000–2008

	Original treatment	Reverse treatment	Original treatment	Reverse treatment	Original treatment	Reverse treatment
Year	–S	+S	–Zn	+Zn	control	Reverse control
2000	10.22	10.01	9.58	9	6.53	9.76
2001	10.44	10.6	9.23	9.38	6.76	9.85
2002	9.25	9.06	9.08	8.79	4.82	9.56
2003	8.26	8.29	7.69	8.23	4.73	8.4
2004	9.44	9.37	9.64	10.11	5.49	9.83
2005	9.41	9.46	9.74	9.94	6	10.1
2006	10.18	10.4	9.81	10.1	5.92	9.93
2007	10.2	9.63	9.72	9.36	5.88	9.77
2008	8.84	9.24	8.92	9.14	4.93	9.05
Mean	9.58	9.56	9.27	9.34	5.67	9.58
$LSD_{0.05}$	0.09	0.16	0.10	0.11	0.56	0.37

Since farmers generally use more N fertilizer and minimum K rate, the latter is depleting rapidly in many areas of Bangladesh (Shil et al. 2016). In the global perspective, K is also depleting by 38.8 kg ha^{-1} year^{-1} (Tan et al. 2005); although its build-up is not uncommon in some areas because of excessive use with specific crops (Bhattacharyya et al. 2006).

The influence of S and Zn on rice productivity is diminishing because of its frequent applications, deposition, and residual effects (Biswas et al. 2018). For example, at the beginning of the long-term trial (1985–2015), the contribution of S and Zn was high for about 7–8 years and then gradually declined. In 2015, we found no contribution of S and Zn for growing rice in Gazipur areas (Haque et al. 2015b). Since rapid industrialization is ongoing in Gazipur areas, depositions of S and Zn are continuously taking place here (Biswas et al. 2018), and thus no effects of added S and Zn were observed for improving rice yields. However, S and Zn deficiencies are found in many parts of the country (Figs. 8.6 and 8.7). It was reported that S status in about 15.62% soils of Bangladesh is very poor (<7.5 ppm); 26.04% low, 14.54% medium, and 43.79% areas are with optimum/high S levels (Fig. 8.6). In about 37.61% areas (score >75) of the country, soil Zn contents are optimum to high (>1.351 ppm), 20.77% areas (40–75 score) are with medium Zn content, and 41.61% soils scored <10 to 40 indicating (Fig. 8.7) that Zn should be added in paddy soils for improving rice yields in Bangladesh.

8.4 Changes in Nutrient Uptake and Use-Efficiency with Rice

Nutrient uptake and its use-efficiency depend on many factors such as variety, nutrient management options, and water management. The use of NPKSZn in balanced proportion showed the highest N, P, K, S, and Zn nutrient uptake than

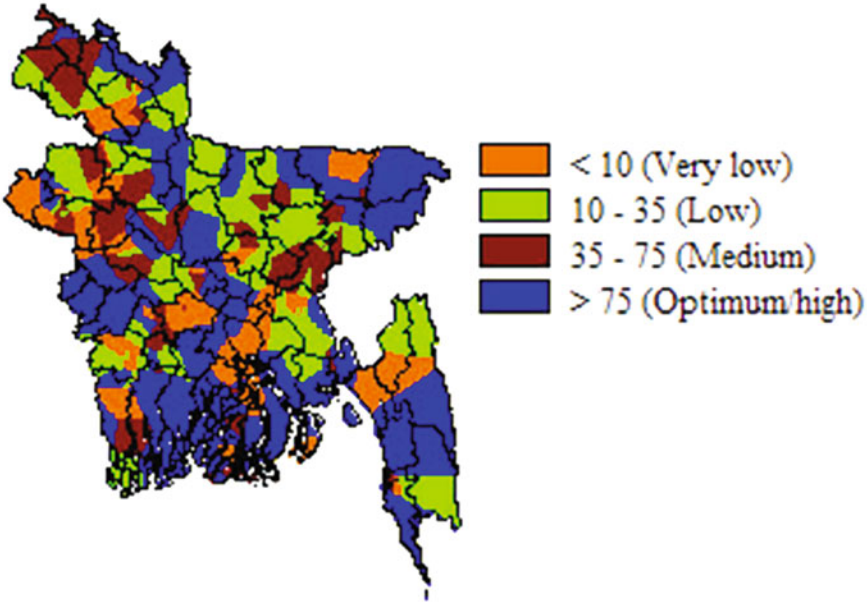


Fig. 8.6 Soil sulphur status in different regions of Bangladesh (Adapted, Biswas et al. 2019b)

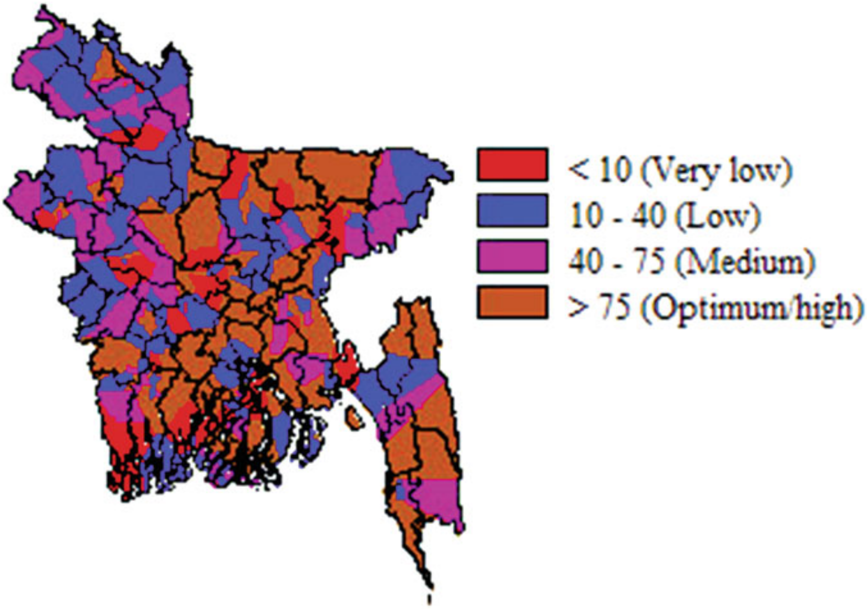


Fig. 8.7 Soil zinc status in different regions of Bangladesh (Adapted, Biswas et al. 2019b)

their omissions. Their uptake patterns suddenly change when nutrients are added to depleted soils. In one trial at BRRI under rice-fallow-rice pattern, it was found that total N uptakes were increased by 79% with N added crop than its missing plots. Total P and K uptakes increased by about 60 and 22%, respectively, with their addition compared to P and K omission plots. Total S and Zn uptake did not vary significantly among the treatments (Table 8.5 and 8.6) due to their deposition in Gazipur areas from industrial sources (Biswas et al. 2018).

Nutrient use efficiency varied slightly because of nutrient addition and their omissions. After 9 years of the trial at BRRI, N, P, S, and Zn use-efficiencies were 34, 41, 14, and 0.32%, respectively, with continuously added fertilizers (Table 8.7). Such scenarios were different when nutrients were added in depleted soils (reverse treatment), in which it was 41 and 35%, respectively, for N and P. Once soil fertility depleted severely in terms of K, S, and Zn, rice crops removed more than added nutrients through fertilizers in a rice-fallow-rice cropping pattern (Table 8.7).

8.5 Contribution of Soil and Added Nutrients

Rice-fallow-rice cropping, the top most ranking pattern, covers about 27% of the net cropped areas in Bangladesh (Nasim et al. 2017). In contrast, the cropping intensity in Bangladesh is 197 (BBS 2018), and nowadays farmers are trying to grow more crops in some regions of the country because of increased food demands. Such activities are providing tremendous pressure on indigenous soil fertility. Now the question is how much our soil is contributing to crop yields and how to adjust the gaps under changing climate. We have determined the contributions of soil and fertilizer at BRRI farm soil (Chhiata clay loam, a member of the fine, Hyperthermic Vertic Endaquept). It was found that in 1985–1989, the contributions of soil and added fertilizers were about 60 and 40%, respectively (Fig. 8.8). However, soil contribution to rice production is decreasing; while on the other hand contribution of fertilizers is increasing during the dry season by about 1% year^{-1}.

8.6 Temperature Rise and Soil Health

The global surface temperature has already been increased by about 1 °C compared to the pre-industrial time and likely to increase further because of climate change impact (IPCC 2018). As air temperature increases, so do soil temperatures and thus influence C mineralization and microbial activities (Naher et al. 2019; Meena et al. 2020a, b) along with many other soil–plant processes. Since soil temperature could be 1–8 °C higher compared to air temperature depending on soil depth and period of the day (Barman et al. 2017), it will be a critical factor for soil productivity in future. In Bangladesh, increase in air temperature is likely to be 1–3 °C in future (Biswas et al. 2017b) indicating that rise in soil temperature may be 2–11 °C in different parts of the country as per Barman et al. (2017). Such an increase in soil temperature would be a severe issue for the maintenance of soil health, especially maintenance of

Table 8.5 Mean nutrient uptakes by rice in a rice-fallow-rice cropping pattern after 9 years of nutrient amendments, BRRI, Gazipur

	Nutrient uptake (kg ha^{-1})							
	Original treatment	Reverse treatment	Original treatment	Reverse treatment	Original treatment	Reverse treatment	Original treatment	Reverse treatment
Nutrient	NPKSZn	All missing	PKSZn (–N)	PKSZn (+N)	NKSZn (–P)	NKSZn (+P)	NPSZn (–K)	NPSZn (+K)
N	105b	53i	63gh	113a	65gh	66 fg	77e	71f
P	25a	14e	18 cd	25a	15e	24ab	21c	18d
K	76bc	44 g	55f	79b	55f	84a	77b	77b
S	11ab	6e	8cde	13a	9bcd	12a	10bc	10bc
Zn	0.5ab	0.3c	0.4bc	0.5ab	0.4bc	0.5ab	0.5ab	0.4bc

Means within a row followed by the same letter do not differ significantly at $P < 0.05$ level using Tukey's HSD test.

Table 8.6 Mean nutrient uptakes by rice in a rice-fallow-rice cropping pattern after 9 years of nutrient amendments, BRRI, Gazipur

	Nutrient uptake (kg ha^{-1})					
	Original treatment	Reverse treatment	Original treatment	Reverse treatment	Original treatment	Reverse treatment
Nutrient	NPKZn (–S)	NPKZn (+S)	NPKS (–Zn)	NPKS (+Zn)	Control	Reverse control
N	88 cd	90 cd	85d	88 cd	62 h	93d
P	24ab	25a	26a	25a	14e	22bc
K	71d	70d	60e	62e	45 g	73 cd
S	8cde	9bcd	8cde	9bcd	7de	10bc
Zn	0.5ab	0.6a	0.5ab	0.5ab	0.3c	0.5ab

Means in a row followed by the same letter do not differ significantly at $P < 0.05$ level using Tukey's HSD test

Table 8.7 Nutrient use efficiency of rice in a rice-fallow-rice cropping pattern under different combinations of nutrients, BRRI, Gazipur

	Nutrient use efficiency (%)				
Treatments	N	P	K	S	Zn
NPKSZn	34	41	−3	14	0.32
Reverse control	41	35	−33	−39	−9

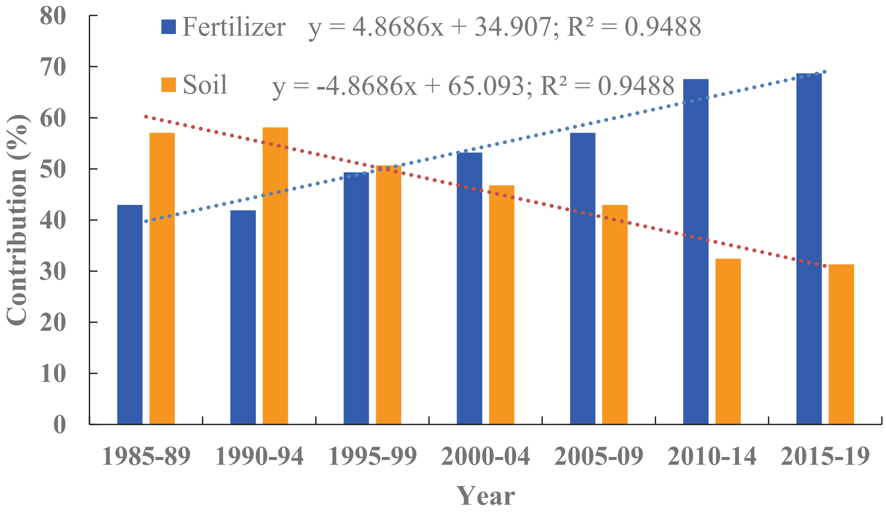


Fig. 8.8 Contribution of soil and fertilizers over the years for dry-season irrigated rice yield, BRRI, Gazipur (Adapted the works at Soil Science Division, BRRI)

SOM. What could be the options to maintain SOC and smooth microbial functioning under the above-stated conditions? Soil amendment could be one of the vital options for maintaining SOC in future.

Fig. 8.9 Loss of carbon from soil as influenced by temperatures and incubation periods; error bar indicates mean standard errors (Data source: Hossain et al. 2017)

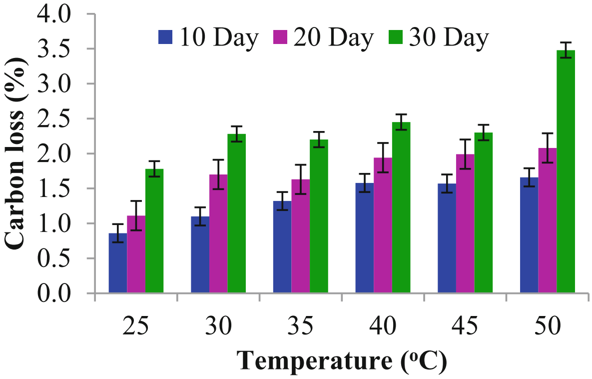
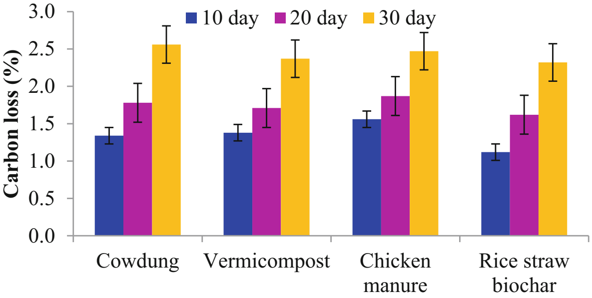


Fig. 8.10 Carbon loss from soil amended with different organic materials; the error bar indicates mean standard errors (Data source: Hossain et al. 2017)



Experimentations at Bangabandhu Sheikh Mujibur Rahman Agricultural University and Bangladesh Rice Research Institute have provided some clues regarding C loss because of soil temperature rise. It was found that C loss will vary by about 1–3.5% depending on temperature regimes (Fig. 8.9). The nature of organic materials incorporated in topsoil also influences C loss from soil (Fig. 8.10). This loss pattern also varies depending on rice growing seasons. The highest C loss was observed in the wet season (T. Aman season) followed by pre-monsoon (Aus season) and dry (Boro) seasons (Fig. 8.11). The loss of C can be minimized in different ways such as the use of recalcitrant organic materials as a soil amendment, growing short-duration varieties, and water management. Alam et al. (2019) also found the highest C sequestration in cow dung (CD) treated plots followed by rice straw, rice husk biochar, poultry manure (PM), vermicompost, and decomposition of those materials were enhanced with N fertilization. This indicates that judicious N management is essential for organic C to build-up in paddy soils along with the nature of soil incorporated organic materials. Incorporation of more refractory organic material into the soil would be the best option to minimize C loss from soil. However, soil surface area also plays an essential role in SOC stabilization (Krishchbaum et al. 2020).

Microbial populations also show variable responses to increased soil temperature depending on fertilizer management practices adopted. Soil bacterial population was

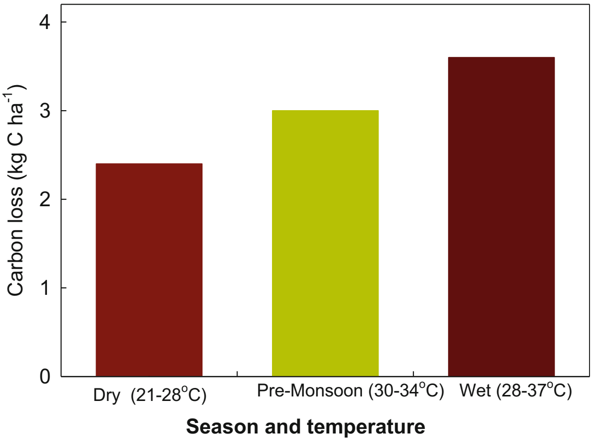


Fig. 8.11 Carbon loss patterns as influenced by seasonal temperature from transplanted rice fields, BRRI, Gazipur (own data)

Table 8.8 Soil bacterial population as influenced by temperature and nutrient sources, BRRI, Gazipur

	28 °C		45 °C	
Incubation (day)	Chemical fertilizer	Integrated nutrient management	Chemical fertilizer	Integrated nutrient management
3	4.8×10^7b	5.0×10^7b	6.0×10^6c	3.6×10^7b
6	3.6×10^7b	3.5×10^7b	4.0×10^6b	7.2×10^6c
9	6.2×10^7b	7.2×10^7b	4.4×10^8a	4.2×10^8a
14	2.9×10^7b	3.6×10^7b	3.0×10^5d	1.2×10^5d
30	9.3×10^4e	5.8×10^4e	2.7×10^4e	4.1×10^4e

Data source: Naher et al. (2019)
Means followed by the same letter are not statistically significant at 5% level of probability

more sensitive to temperature change than fungi and actinomycetes (Naher et al. 2019). They also reported that phosphate solubilizing bacteria were more resistant to high temperature than free-living N-fixing bacteria. Bacteria population showed a differential response to temperature depending on nutrient sources, especially with integrated nutrient management system (Table 8.8) indicating that we have to follow such practices to adapt climate change impact in future.

8.7 Nutrient Mining/Build-Up

Soil fertility in Bangladesh, as a whole, is deficient in many cases for sustained crop production (Biswas et al. 2019b). Cultivation in such soils with or without balanced fertilizers is rendering it beyond the limit of recuperation in some cases. So, it is imperative to find out crop response under long-term missing nutrients conditions. From one investigation, it was found that continuous rice cultivation with chemical fertilizers for 9 years significantly ($p < 0.05$) deteriorated exchangeable K and SOC content (Table 8.9). Continuous applications of P, S, and Zn fertilizers for 9 years significantly ($p < 0.05$) increased soil available P, S, and Zn. While on the other hand, the continuous missing of tested elements for 15 years and then their application as reverse treatments for 9 years, soil nutrient status did not recover fully and even there was a significant negative C balance (-66 kg C ha^{-1}, $p < 0.05$) compared to NPKSZn (-24 kg C ha^{-1}) treatment in the rice-fallow-rice system. It means negative nutrient balance deteriorates soil quality as well as increased carbon dioxide (CO_2) concentration to the atmosphere. Since SOM is generally low in soils of Bangladesh due to chemical fertilizer applications in most cases (Biswas et al. 2019b), the continuous addition of different types of decomposable organic materials (rice straw, vermicompost, CD, PM, cover crop biomass, etc.) might help in improving soil health such as soil aggregate stability, SOC and C sequestration and thus will reduce GHGs emission, GWP and increase capturing of CO_2 from the atmosphere with better crop growth (Haque et al. 2017c, 2020).

8.8 Recuperation of Soil Fertility

Different practices can be adopted for rejuvenating soil fertility. Some of the practices are discussed in the following sub-heads.

8.8.1 Organic Amendment: Alternate Sources of Nutrients

Rice grain yields were significantly higher (31–45%) under organic amendments than with chemical fertilizer treatment, but the yield also varied significantly between CD and PM amendments under integrated plant nutrient system for the rice-fallow-rice pattern. Only chemical fertilizer treatment showed significantly lower rice yield than organic amended treatment in 2014–2019 (Fig. 8.12). Another vital point that needs to be considered is the recycling of decomposable organic substances as nutrient sources along with C sequestration. Use of organic materials in the paddy field can result in net positive ecosystem C budget (Fig. 8.13). While on the other hand, balanced fertilization as integrated nutrient management is a good practice for reducing GWP and enhancing CO_2 fixation during photosynthesis for higher biomass production. It was observed that use of different types of organic materials could reduce GHGs emission, increase grain yield of rice, and improve SOC budget (Haque et al. 2019b). While on the other hand, the use of chemical fertilizers alone was responsible for decreased SOC, indicating that they were liable for higher GWP. So, organic and inorganic fertilizer management could be a good option for reducing GHGs, GWP and to increase SOC balance along with the fulfillment of food demand.

Table 8.9 Post-harvest soil properties as influenced by fertilizer management after 9 years, BRRI, Gazipur

	Nutrient content						
Treatments	N (%)	Available P (ppm)	Exchangeable K (me100 gm soil)	Available S (ppm)	Available Zn (ppm)	OC ($g\ kg^{-1}$)	Soil C balance ($kg\ ha^{-1}$)
NPKSZn	0.13	30	0.14	28	5.0	12.0	−24
Reverse control	0.12	24	0.11	30	5.2	11.8	−66
Initial soil	0.09	9.8	0.18	9.00	3.00	12.2	–

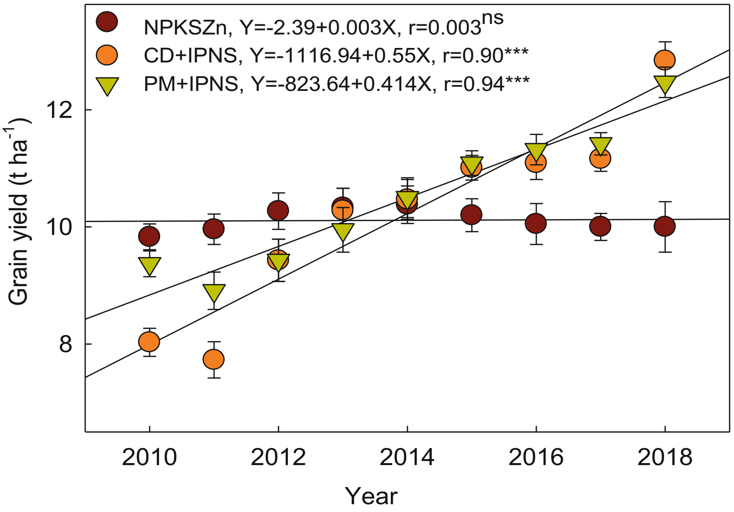


Fig. 8.12 Grain yield as influenced by soil amendment for 9 years, BRRI, Gazipur

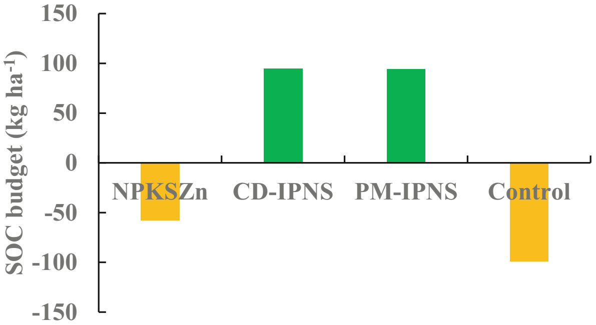


Fig. 8.13 Soil organic carbon stock as influenced by soil amendment for 9 years, BRRI, Gazipur

8.8.2 Choice of Suitable Cropping Pattern

There are many agriculture managements practices suitable to maintain SOC if adopted. We have evaluated the performances of the introduced mustard crop in between T. Aman and Boro rice along with the utilization of residual soil fertility. It was found that T. Aman-Mustard-Boro cropping influences net C budget positively (Fig. 8.14) because of net primary production C added by rice and mustard. However, rice-fallow-rice cropping pattern showed a negative C balance due to more C loss through CH_4-C and CO_2-C emission. It was also observed that rice-fallow-rice cropping pattern with chemical fertilizer application is the cause of increase C output than C input (Haque et al. 2017c) resulting in negative soil C balance.

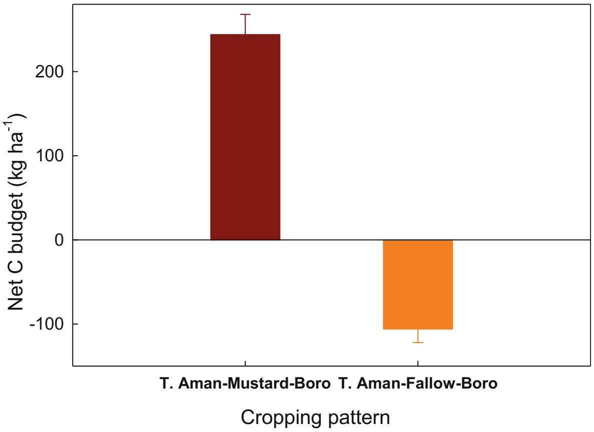


Fig. 8.14 Net carbon budget as influenced by cropping patterns in Bangladesh

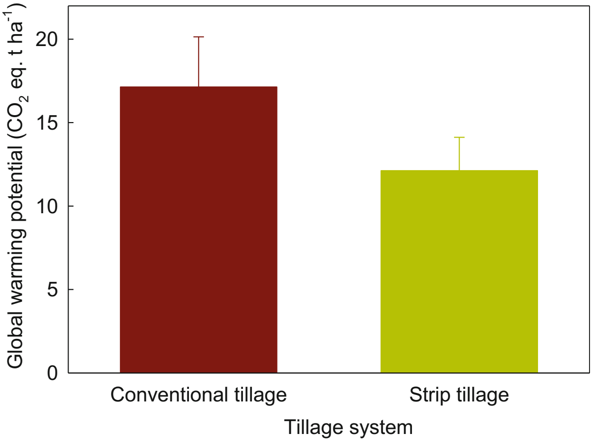


Fig. 8.15 Total GWP as influenced by different tillage systems under T. Aman-Mustard-Boro cropping pattern in Bangladesh

8.8.3 Tillage Practices

Tillage practices are generally adopted to have good tilth under upland conditions and making impervious layers for preventing downward water movement with wetland rice culture along with facilitating weed control efficiencies. Although tillage systems are essential for crop production, reduced tillage operation can miniize C loss, and to increase C balance under changing climate (Meena et al. 2020a). With this view, we have evaluated strip tillage and conventional tillage practices for the establishment of the mustard crop. It was found that strip-tillage reduced about 33% GWP and 37% C loss under T. Aman-Mustard-Boro cropping pattern than conventional tillage system (Figs. 8.15 and 8.16). So, strip-tillage based conservation agriculture practices is an important management strategy for reducing GWP and in increasing soil C balance (Krauss et al. 2017).

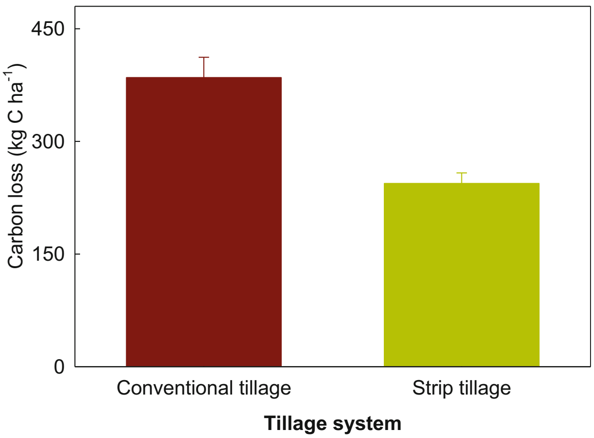


Fig. 8.16 Carbon loss as influenced by conventional and strip tillage systems under T. Aman-Mustard-Boro cropping pattern in Bangladesh

8.9 Conclusions and Recommendations

Long-term use of only chemical fertilizers cannot maintain rice yield productivity as well as soil fertility. The contribution of soil to rice productivity in a rice-fallow-rice system is decreasing that necessitate the integrated use of nutrients from organic and inorganic sources not only to alleviate rice production but also to sequester carbon. The impact of missing nutrient elements on rice yield and soil fertility varied depending on nutrient management options. For example, missing phosphorus for about 10–12 years was not much influential on grain yield of rice, but soil reserve was diminishing. We have seen the effect of added nutrients through reversing treatments of tested nutrients after 15 years that continued for 9 years on soil fertility and grain yield of rice. Although grain yield achieved was almost identical with regularly fertilized plots, reversing treatment with depleted soils was inadequate to recuperate soil fertility specifically for potassium, sulphur, and zinc. So, we have to take special care for soil fertility improvement of severely depleted soils in term of potassium, sulphur, and zinc status for sustained rice productivity.

8.10 Future Perspectives

Considering increased global food demands under changing climate, especially with rising temperature in the near future, crop production may face dire consequences of reduced productivity. Some management strategies, as stated below, might help maintain soil carbon balance as well as crop productivity.

- Consciousnesses build-up among different stakeholders for balanced chemical fertilizer application.
- Farmers' training arrangement for the use of organic and inorganic nutrient sources.
- Motivational tools created and price incentives for a better harvest.
- Rice straw up to 20 cm incorporated into rice soil.
- Inclusion of leguminous crops in crop rotations.
- The popularization of reduced tillage practices.
- Nutrient use efficient along with less CH_4 emitting rice varieties need to be developed and popularized among farmers.
- Tune-up of fertilizer doses regularly with special emphasis on soil micronutrients status.

References

ADRC (Asian Disaster Reduction Center) (2018) Information on disaster risk reduction of the member countries. http://www.adrc.Asia/nation information.Php?Nation Code=50& Lang= en& Mode= country

Ahmmed S, Jahiruddin M, Razia MS, Begum RA, Biswas JC, Rahman ASMM, Ali MM, Islam MKMS, Hossain MM, Gani MN, Hossain GMA, Satter MA (2018) Fertilizer recommendation guide-2018, vol 1215. Bangladesh Agricultural Research Council, Dhaka, p 223

AIS (2016) Krishi diary 2016. Agricultural Information Service, Dhaka

Alam MA, Rahman MM, Biswas JC, Akhter S, Maniruzzaman M, Choudhury AK, Jahan MAHS, Miah MMU, Sen R, Kamal MZU, Mannan MA, Shiragi HK, Kabir W, Kalra N (2019) Nitrogen transformation and carbon sequestration in wetland paddy field of Bangladesh. Paddy Water Environ 5:1–12. https://doi.org/10.1007/s10333-019-00693-7

Bajiya R, Lakhran H, Kumar S, Seema (2017) Biochar for enhancing agricultural sustainability under climate change. Int J Curr Microbiol App Sci 6(2):1876–1883

Barman D, Kundu DK, Pal S, Chakraborty AK, Jha AK, Mazumdar SP, Saha R, Bhattacharyya P (2017) Soil temperature prediction from air temperature for alluvial soils in lower Indo-Gangetic plain. Int Agrophys 31:9–22

BBS (Bangladesh Bureau of Statistics) (2017) Statistical year book of Bangladesh. Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka

BBS (Bangladesh Bureau of Statistics) (2018) Year book of agriculture statistic. Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka

Bhattacharyya R, Prakash V, Kundu S, Ghosh BN, Srivastva AK, Gupta HS (2006) Potassium balance as influenced by farmyard manure application under continuous soybean–wheat cropping system in a Typic Haplaquept. Geoderma 137:155–160

Biswas JC, Maniruzzaman M, Sattar MA, Neogi MG (2008) Improvement of rice yield through fertilizer and cultural management at farmer's field. Ban Rice J 13:9–14

Biswas JC, Haque MM, Saha PK (2017a) Rice yield potential under unfavorable soil ecosystems in Bangladesh. Asian J Soil Sci Plant Nutr 1:1–10

Biswas JC, Maniruzzaman M, Naher UA, Haque MM, Rahman MB, Rahman MM, Miah MMU, Choudhury AK, Akhter S, Ahmed F, Hamid MA, Kalra N, Furuya J (2017b) Future climate change scenarios and anticipated performance of major cereals in Bangladesh. Int J Agric Environ Res 3:4124–4148

Biswas JC, Haque MM, Akter M, Hossain ATMS, Khan FH, Baki MZI, Sarker ABS, Islam MR (2018) Element composition of the atmospheric depositions in Bangladesh. J Environ Protec 9:948–956

Biswas JC, Haque MM, Maniruzzaman M, Ali MH, Kabir W, Kalra N (2019a) Natural hazards and livestock damage in Bangladesh. Nat Hazards 99:705–714. https://doi.org/10.1007/s11069-019-03768-0

Biswas JC, Kalra N, Maniruzzaman M, Haque MM, Naher UA, Ali MH, Kabir W, Rahnamayan S (2019b) Soil fertility levels in Bangladesh for rice cultivation. Asian J Soil Sci Plant Nutr 4:1–11

Biswas JC, Haque MM, Saha PK (2019c) Soil calcium, magnesium and potassium status: concern for rice production in Bangladesh under unfavorable ecosystems. In: New perspectives in international plant and soil research, vol 1. Book Publisher International, Brazil, Print ISBN: 978-81-940613-9-7, eBook ISBN: 978-93-89246-29-2

Emran SA, Krupnik TJ, Kumar V, Ali MY, Pittelkowa CM (2019) Agronomic, economic, and environmental performance of nitrogen rates and source in Bangladesh's coastal rice agroecosystems. Field Crop Res 241:107567

Haque MM, Kim SY, Pramanik P, Kim GY, Kim PJ (2013) Optimum application level of winter cover crop biomass as green manure under considering methane emission and rice productivity in paddy soil. Biol Fertil Soils 49:487–493

Haque MM, Saleque MA, Shah AL, Wangmode TR (2014) Effects of long-term fertilization and soil native nutrient on rice productivity in double rice cultivation system. Aperito J Biochem Biochem Tech 1:103

Haque MM, Kim SY, Kim GW, Kim PJ (2015a) Optimization of removal and recycling ratio of cover crop biomass using carbon balance to sustain soil organic carbon stocks in a mono-rice paddy system. Agric Ecosyst Environ 207:119–125

Haque MM, Saleque MA, Shah AL, Biswas JC, Kim PJ (2015b) Long-term effect of sulfur and zinc fertilization on rice productivity and nutrient efficiency in double rice cropping paddy in Bangladesh. Commun Soil Sci Plant Anal 46:2877–2887

Haque MM, Saleque MA, Shah AL (2015c) Effect of long-term fertilization on rice productivity and nutrient efficiency under double cropping system. Aperito J Biochem Biochem Tech 1:105

Haque MM, Kim SY, Ali MA, Kim PJ (2015d) Contribution of greenhouse gas emissions during cropping and fallow seasons on total global warming potential in mono-rice paddy soils. Plant and Soil 387:251–264

Haque MM, Biswas JC, Kim SY, Kim PJ (2016) Suppressing methane emission and global warming potential from rice fields through intermittent drainage and green biomass amendment. Soil Use Manage 32:72–79

Haque MM, Akter M, Biswas JC, Islam A, Saha PK, Shah AL (2017a) Long-term effect of organic and inorganic nutrients on yield and yield trend of lowland rice. Annual research review workshop 2014–15, 2015–16, 2016–17. Soil Science Division, Bangladesh Rice Research Institute, Gazipur, p 24, 36, 43

Haque MM, Biswas JC, Maniruzzaman M, Choudhury AK, Naher UA, Hossain MB, Akhter S, Ahmed F, Kalra N (2017b) Greenhouse gas emissions from selected cropping patterns and adaptation strategies in Bangladesh. Int J Develop Res 7:16832–16838

Haque MM, Biswas JC, Kim SY, Kim PL (2017c) Intermittent drainage in paddy soil: ecosystem carbon budget and global warming potential. Paddy Water Environ 15:403–411

Haque MM, Biswas JC, Islam MR, Islam A, Kabir MS (2019a) Effect of long-term chemical and organic fertilization on rice productivity, nutrient use-efficiency, and balance under a rice-fallow- rice system. J Plant Nutr 42:2901–2914

Haque MM, Biswas JC, Akter M, Maniruzaman M, Kabir MS (2019b) Carbon budget and aggregate stability of paddy soil under continuous organic amendment. Commun Soil Sci Plant Anal 50:1829–1837. https://doi.org/10.1080/00103624.2019.1635148

Haque MM, Shaha AL, Biswas JC, Islam MR, Islam A, Naher UA (2019c) Effect of missing nutrient elements on grain yield of wet season rice in Bangladesh. Am J Plant Sci 10:631–639

Haque MM, Biswas JC, Hwang HY, Kim PJ (2020) Annual net carbon budget in rice soil. Nutr Cycl Agroecosyst 116:31–40. https://doi.org/10.1007/s10705-019-10029-w

Hossain MB, Rahman RM, Biswas JC, Miah MMU, Akhter S, Maniruzzaman M, Choudhury AK, Ahmed F, Shiragi MHK, Kalra N (2017) Carbon mineralization and carbon dioxide emission from organic matter added soil under different temperature regimes. Int J Recycl Org Waste Agri 6:311–319. https://doi.org/10.1007/s40093-017-0179-1

Ibrahim M, Cao CG, Zhan M, Li CF, Iqbal J (2015) Changes of CO_2 emission and labile organic carbon as influenced by rice straw and different water regimes. Int J Environ Sci Tech 12:263–274

IPCC (Intergovernmental Panel on Climate Change) (2018) Global warming of 1.5°C, an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch

Jakhar SR, Kumar S, Jangir CK, Meena RS (2017) The role of mycorrhizal relationship in sustainable manner towards plant growth and soil fertility. J Curr Microb Appl Sci 3(4):19–24

Kabir MS, Salam MU, Chowdhury A, Rahman NMF, Iftekharuddaula KM, Rahman MS, Rashid MH, Dipti SS, Islam A, Latif MA, Islam AKMS, Hossain MM, Nessa B, Ansari TH, Ali MA, Biswas JK (2015) Rice vision for Bangladesh: 2050 and beyond. Bang Rice J 19:1–18

Krauss M, Ruser R, Muller T, Hansen S, Mader P, Gattinger A (2017) Impact of reduced tillage on greenhouse gas emission and soil carbon stocks in an organic grass-clover ley- winter wheat cropping sequence. Agric Ecosyst Environ 239:324–333

Krishchbaum MUF, Moinet GYK, Hedley CB, Beare MH, McNally SR (2020) A conceptual model of carbon stabilization based on patterns observed in different soils. Soil Biol Biochem 141:107683. https://doi.org/10.1016/j.soilbio.2019.107683

Kumar S, Karaliya SK, Chaudhary S (2017) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. J Curr Microb Appl Sci 6 (3):142–151

Kumar S, Meena RS, Lal R (2018) Role of legumes in soil carbon sequestration. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 109–138. https://doi.org/10.1007/978-981-13-0253-4_4

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, Singapore, pp 337–375. https://doi.org/10.1007/978-981-13-7264-3_10

Lee CH, Kang UG, Park KD, Lee DK, Kim PJ (2008) Long-term fertilization effects on rice productivity and nutrient efficiency in Korean paddy. J Plant Nutr 31:1496–1506

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena RS, Gogoi N, Kumar S (2017) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359

Meena RS, Kumar S, Yadav GS (2019) Soil carbon sequestration in crop production. In: Meena RS (ed) Nutrient dynamics for sustainable crop production. Springer, Singapore, pp 1–39. https://doi.org/10.1007/978-981-13-8660-2_1

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Landarzt 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Naher UA, Sarker IU, Jahan A, Maniruzzaman M, Choudhury AK, Kalra N, Biswas JC (2019) Nutrient mineralization and soil biology as influenced by temperature and fertilizer management practices. Sains Malay 48:735–744

Nasim M, Shahidullah SM, Saha A, Muttaleb MA, Aditya TL, Ali MA, Kabir MS (2017) Distribution of crops and cropping patterns in Bangladesh. Bang Rice J 21:1–55

Saha PK, Islam S, Islam MN, Biswas JC, Haque MM (2016) Soil plant nutrient status under intensive rice-farming systems in unfavourable eco-system of Bangladesh. Intl J Biol Pharma Sci 2:1–11

Saleque MA, Abedin MJ, Bhuiyan NI, Zaman SK, Panaullah GM (2004) Long-term effects of inorganic and organic fertilizer sources on yield and nutrient accumulation of lowland rice. Field Crop Res 86:53–65

Shil NC, Saleque MA, Islam MR, Jahiruddin M (2016) Soil fertility status of some of the intensive crop growing areas under major agro-ecological zones of Bangladesh. Bangladesh J Agri Res 41:735–757

Sihag SK, Singh MK, Meena RS, Naga SR, Bahadur S, Gaurav YRS (2015) Influences of spacing on growth and yield potential of dry direct seeded rice (*Oryza sativa* L.) cultivars. Ecoscan 9 (1–2):517–519

Sihi D, Dari B, Sharma DK, Pathak H, Nain L, Sharma OP (2017) Evaluation of soil health in organic vs. conventional farming of basmati rice in North India. J Plant Nutr Soil Sci 180:389–406

Swarup A, Wanjari RH (2000) Three decades of all-India co-ordinated research project on long-term fertilizer experiments to study changes in soil quality, crop productivity and sustainability. Indian Institute of Soil Science, Bhopal

Tan ZX, Lal R, Wiebe KD (2005) Global soil nutrient depletion and yield reduction. J Sustain Agric 26:123–146

Timsina J, Wolf J, Guilpart N, van Bussel LGJ, Grassini P, vanWart J, Hossaind A, Rashid H, Islam S, van Ittersum MK (2018) Can Bangladesh produce enough cereals to meet future demand? Agr Syst 163:36–44

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan region, India. Int J Chem Stud 5(4):1558–1560

Yadvinder S, Bijay S, Timsina J (2005) Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. Adv Agron 85:269–407

Zhang MK, Fang LP (2007) Effect of tillage, fertilizer and green manure cropping on soil quality at an abandoned brick making site. Soil Tillage Res 93:87–93

Organic Sources and Tillage Practices for Soil Management

9

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Abstract

Soil is the most valued natural resource, which needs to be used until the existence of the world for our food production. There is a limited option to bring new land under crop cultivation. The finite land resource is decreasing continuously due to a new settlement, industrial, and other development activities. Intensive agriculture ensured food security, which, however, exerts huge pressure on arable land through increased frequency of crop cultivation, repeated tillage, and indiscriminate use of unbalanced agrochemicals. The resultant effects of long-term intensive agriculture are the depletion of organic matter (OM) and degradation of soils, which attributes to lower use efficiencies of agricultural inputs. It is anticipated that 60% more yields of cereals will be needed by 2050 contrasted with the current level. Because of poor soil health, it has become a great challenge to keep increased food production onwards. If the productive capacity of soils could not be maintained, the present civilization must be collapsed. Therefore, the soil needs to be kept alive by adding locally available organic amendments and adopting conservation tillage practices. Soil carbon (C) is the fuel and driving force of ecosystem functions. Application of organic amendments increases soil C, builds soil structure, enriches biological diversity, and contributes to reducing inorganic fertilizers in crop production. Rice straw is the most available residue in many countries of the world, which increases soil aggregate stability, organic C, and cation exchange capacity by 27.8, 45.5, and 27.2%, respectively, compared to sole inorganic fertilizer application. Poultry manure and cow dung were found effective to reduce soil acidity, which depends on the rates and frequency of their application. Conservation tillage like no-till, reduced tillage, and strip-tillage, etc. diminishes mineralization of OM and increases C accumulation in soil. No-till with residue retention has global demand, which is one of the best options of increasing soil C. No-till system alone can save about 70% energy and fuel consumption compared to traditional tillage. Rotation of crops, retention of residues, and adoption of other suitable resource conservation strategies further ensure good soil health and its productive capacity. The combined adoption of organic amendments and conservation tillage can revitalize degraded soils and bring multiple benefits including agricultural sustainability and mitigation of climate change.

Keywords

Crop residues · Intensive agriculture · Organic fertilizer · Soil health · Sustainability

Abbreviations

AEC	Anion exchange capacity
Al	Aluminum
AMF	Arbuscular mycorrhizal fungi
B	Boron
BNF	Biological nitrogen fixation
BSMRAU	Bangabandhu Sheikh Mujibur Rahman Agricultural University
C	Carbon
Ca	Calcium
CA	Conservation agriculture
$CaCO_3$	Calcium carbonate
cc	Cubic centimetre
CD	Cow dung
CEC	Cation exchange capacity
CFU	Colony forming units
CH_4	Methane
Cl	Chlorine
Co	Cobalt
CO_2	Carbon dioxide
CP	Compost
Cu	Copper
FAO	Food and Agriculture Organization
Fe	Iron
FRG	Fertilizer recommendation guide
FYM	Farmyard manure
$g\ cc^{-1}$	Grams per cubic centimetre
$g\ kg^{-1}$	Grams per kilogram
GHG	Greenhouse gas
GM	Green manure
H	Hydrogen
$H_2PO_4^-$	Phosphate
HCO_3^-	Bicarbonate
K	Potassium
$mg\ kg^{-1}$	Milligrams per kilogram
Mg	Magnesium
mm	Millimetre
Mn	Manganese
Mo	Molybdenum

MT	Minimum tillage
N	Nitrogen
N_2O	Nitrous oxide
Na	Sodium
NH_4^+	Ammonium
Ni	Nickel
NO_2^-	Nitrite
NO_3^-	Nitrate
NUE	Nitrogen use efficiency
O	Oxygen
OC	Organic carbon
OH^-	Hydroxide
OM	Organic matter
P	Phosphorus
Pg	Peta gram
PGPF	Plant growth promoting fungi
PGPM	Plant growth promoting microbes
PGPR	Plant growth promoting rhizobacteria
PM	Poultry manure
RHB	Rice husk biochar
RS	Rice straw
RT	Reduced tillage
S	Sulphur
SDGs	Sustainable development goals
Si	Silicon
SO_4^{-2}	Sulphate
SOC	Soil organic carbon
SOM	Soil organic matter
ST	Strip tillage
$t\ ha^{-1}$	Ton per hectare
TT	Traditional tillage
UN	United Nations
Va	Vanadium
VC	Vermicompost
WHC	Water holding capacity
Zn	Zinc

9.1 Introduction

Soil is not only our existence, it is the harbour of entire lives including flora and fauna in the earth. It feeds the global population including all the living beings through producing foods, while the future food production for the ever-burgeoning population depends on soil health (Fan et al. 2011; FAO 2015; Gannett et al. 2019). Kibblewhite et al. (2007) described soil health as an outcome of integrated management of soil and crops, which reveals the ability of soil to restore and replenish fertility and productive capacity on a sustained basis. Nowadays, degradation of soil health is one of the burning issues in agriculture globally. Farmers and commercial entrepreneurs follow traditional tillage (TT) practice and apply an excess amount of inorganic fertilizers. The necessity of organic fertilizers in sustaining soil fertility and crop productivity is ignored in many cases. Sole application of inorganic fertilizers degrades soil health and ultimately soil becomes less productive (Rahman 2014; Drakopoulos et al. 2016). Moreover, our agricultural land is annually decreasing by 1% due to anthropogenic activities like human settlement, industrialization, brickfields, roads construction, etc. (Rahman et al. 2020). World population is increasing in one hand, while the land resource is decreasing in other hand. Of the total global land area, the global agricultural land is 37.431%, and most of the best land is already taken under agriculture practices, therefore, the expansion of new land for agriculture is almost impossible (World Bank 2016). FAO (2009) reported that for an increment of 2.3 billion peoples by 2050, only cereal demand (both for man and animal) will be increased from 2.1 billion tons to 3 billion tons. It will be needed to produce 60% more yields of cereal crops by 2050 then the present yields (FAO 2015; Rosenstock et al. 2016). Climate change increases soil erosion and atmospheric temperature and lowers water tables, which further make difficult to produce more foods and feed the world. In this situation, it is really a great challenge to produce increased foods keeping our soil alive and productive for the future generation. Protection and conservation of soil, land, and water resources and efficient utilization of production inputs should receive high priority to meet our food requirements (Gupta and Sayre 2007).

Factor productivity of different agricultural inputs like land, fertilizers, irrigation water, etc. decreases and ultimately attributed to lower resource use efficiency (Rahman 2013; Alam et al. 2019). The global cereal production vs nitrogen use efficiency (NUE) described by Tilman et al. (2002) is depicted in Fig. 9.1. The cereal production increases almost in a linear fashion from 1960 to 1995 (Fig. 9.1a), while NUE radically decreases from 1960 until 1980 (Fig. 9.1b). After 1980, NUE follows almost stable state, which reveals that the further increment only in nitrogen (N) fertilizer application may not increase cereal production unless attention is paid towards soil health management adopting resource conservation strategies. This has been further endorsed by Alam et al. (2019), where it was reported that rice (*Oryza sativa* L.) yields and carbon (C) sequestration increased due to different management practices. On the other hand, raising N fertilizer application from 100 to 150 kg ha^{-1}, rice yield was not increased, while C sequestration decreased by 25%.

Application of different amendments and adoption of conservation tillage practices may bring a radical change in soil health restoration. Reduced tillage (RT) and addition of different organic amendments like cow dung (CD), poultry manure (PM), rice straw (RS), compost (CP), farmyard manure (FYM), green manure (GM), etc. are practised globally to increase soil microbial abundance and their diversity, improve soil properties, and ensure a healthy soil, which contributes in sustaining crop yield (Beare et al. 1994; Rahman et al. 2016; Wang et al. 2016). It is reported that addition of organic matter (OM) to the soil promotes soil structural

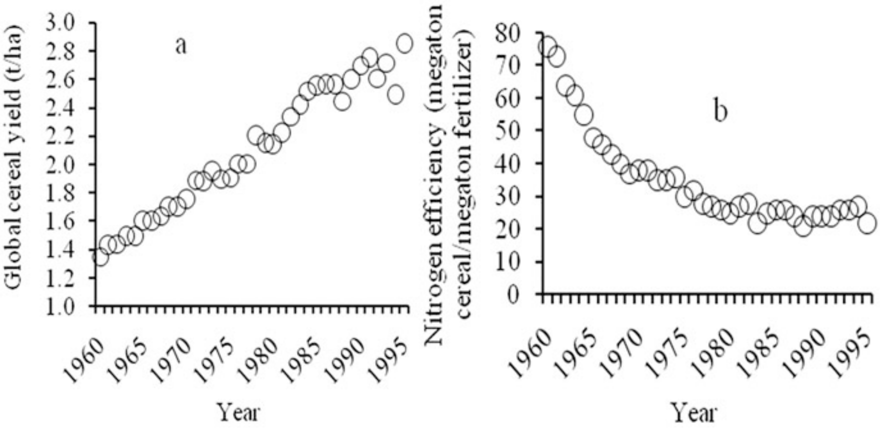

Fig. 9.1 Trends of global cereal production (**a**), and nitrogen use efficiency (**b**). (Adopted, Redrawn from Tilman et al. 2002)

stability, microbial diversity, and nutrient supplying capacity of the soil (Trinsoutrot et al. 2000; Manzoni and Porparato 2009; Roy et al. 2019).

Tillage operation is a turmoil of soil and has long-term effects of conventional or traditional tillage (TT) to soil environment can be compared with the effects of the earthquake, hurricane tornadoes, etc. Long-term practice of conventional tillage substantially degrades soil health, reduces soil nutrients and crop yields, and finally appears as a threat to agricultural and environmental sustainability (Hafeez-ur-Rehman et al. 2015). Conversely, conservation tillage like no-till, reduced tillage (RT), minimum tillage (MT), strip-tillage (ST), etc. decreases OM decomposition and soil gain more C, thus conserving soil fertility and agricultural sustainability (Six et al. 2002).

Carbon contents in soils of the tropical and subtropical regions are inherently low (Mandal et al. 2007). This is because of favourable climatic conditions for the faster microbial decomposition of organic materials. In such a fragile production system application of organic amendments to crop fields makes worthy use of natural resources. Application of organic fertilizers shrinks the requirement of mineral fertilizers and improves nutrient use efficiency in crop production (Rahman 2013; Antonious 2016; Rahman et al. 2020). Resource use efficiency of agricultural inputs must be increased through proper and modern soil and crop management practices. Results from the different investigation revealed that use of C-based amendments in crop fields improves soil aggregates, moisture contents, NUE, and microbiological diversity and their activities, which ultimately influences soil fertility and productivity (Antonious 2016; Roy et al. 2019). Organic amendments slowly release nutrients to soils for crops being grown in several crop seasons. Organic fertilizers contain sugars and amino acids, which enhance the microbiological activity, and thereafter, associated soil fertility.

9.2 Soil Under Intensive Agriculture

Intensive agriculture is an option to get maximum crop yields from a unit area of land using a higher amount of chemical fertilizers and synthetic pesticides creating environmental hazards (Scotti et al. 2015). Such exposures on agricultural land change soil quality in terms of fertility reduction and biodiversity loss in the agroecosystems. It is stated that since the previous 60 years, the worldwide usage of N fertilizers increased by seven-folds, while the usages of phosphorus (P) fertilizers increased by 3.5 folds, which indicates that the traditional or extensive agriculture moving fast towards intensive agriculture (Tilman et al. 2002). Intensive agriculture is a capital- and a labor-intensive system, where the frequency of cultivation is high and the land is subject to deterioration of physicochemical and biological properties (Greenland 1977). About 2–3 crops and even four crops are grown in the same land in a yearly sequence to increase cropping intensity. Four-crops cropping pattern like rice-rice-rice-mustard is practised in Bangladesh to increase crop productivity. Such intensification in agricultural production systems contributed to a large increase in crop yields and ensured food and nutrition security of the global population. However, agricultural intensification caused for severe ecological damages like soil structural degradation, water shortages, fertilizers, and pesticide pollution in the surface and underground water, eutrophication of surface water of lakes, streams, rivers etc., loss of soil microbes, and increasing costs of production (Hunke et al. 2015). Because of the intensive tillage, soils have become physically disturbed. This caused the disintegration of soil aggregates, faster decomposition of soil organic matter (SOM), and finally, soil health and crop quality deteriorated (Paustian et al. 2000; Schiesari et al. 2013). It is reported that the shared effect of intensive agriculture and climate change can severely degrade fertility of soils, and reduce yields of many crops and disrupt the ecosystem functions (Paustian et al. 2000; Rahman et al. 2017). Reduction in crop yields because of soil and land degradation is evinced in Africa, Asia, and Latin America (Kaiser 2004).

9.3 Sustainable Soil Management

Intensive agriculture certainly ensured food security of the global population (Norris and Congreves 2018). A higher amount of fertilizers, more tillage and frequent supply of irrigation water are needed to produce high crop yields under intensive agriculture. Such injudicious agricultural activities seriously degraded soil and environment, thus the ecosystem has lost its capacity to function properly (Norris and Congreves 2018; Meena et al. 2020a). Sustainable management of soils is a great challenge in agriculture of the twenty-first century (Meena and Lal 2018). The key challenge of sustainable agriculture is to conserve soil and land for fostering ecosystem services while ensuring a healthy soil. Agricultural sustainability depends on soil quality, which is defined as the ability of soil to perform its function effectively within ecosystem boundary that maintain plant and animal productivity, protect air and water attributes, care human health, and conserve their habitats

Table 9.1 Rice yield and carbon sequestration as affected by different organic materials (Adapted, Alam et al. 2019)

Treatments	Rice grain ($t\ ha^{-1}$)	Initial soil C (%)	C at crop harvest (%)	C sequestration ($t\ ha^{-1}$)
RS	5.66bc	0.77ab	0.85a	1.30ab
VC	5.89ab	0.80a	0.86a	1.02b
RHB	5.24c	0.75ab	0.81ab	1.23ab
CD	5.69abc	0.70c	0.77b	1.45a
PM	6.32a	0.71bc	0.76b	1.13ab
CV (%)	9.02	8.03	6.40	25.87

RS rice straw, *VC* vermicompost, *RHB* rice husk biochar, *CD* cow dung, *PM* poultry manure, *C* carbon, *Seq.* sequestration

(Karlen et al. 1997). Adoption of conservation agriculture (CA) is essential to increase and maintain soil quality. Sustainable agriculture is synonymous with CA, which relies on appropriate management activities of soils and crops. In sustainable or conservation agriculture, there are three pillars viz., no-till/zero till, continuous crop residue retention/cover crops, and legume-based crop rotations. Conservation agriculture greatly depends on soil organic carbon (OC) as OM. Soil OM is one of the vital components that govern soil physical, chemical, and microbiological properties. Lal (2004) reported that the global soil contains 2500 Peta gram (Pg) of C, which is four times higher than that of the biotic pool and three times that of atmospheric C pool. Global soils annually release about 68–80 Pg of C to the atmosphere because of OM decomposition and plant root respiration, which is ten times higher emission compared to fossil fuel burning (Raich et al. 2002; Powlson et al. 2011). Alam et al. (2019) found that C sequestration potential of different organic amendments is highly variable, which depends mainly on its mineralization stage, while such amendments sustain crop yield (Table 9.1). Therefore, if soil and crop management practices can bring a small increment in soil C it would have a hugely positive effect on soil health and environmental sustainability.

Soil OM is a hub for regulating different functions of soil and dealing with CA. Soil health is reliant on the performance of C transformations, nutrient dynamics, soil structural development, and microbial diversity and their abundance, which further largely depends on conservation tillage, and organic amendments (Fig. 9.2). There are several actions and interactions and multiple benefits of adoption of no-till/RT and supply of organic materials to the soil. Such approaches are playing significant roles in developing soil aggregates, conserving nutrients, and increasing microbial diversity for improving soil health, and ultimately driving agriculture towards a sustainable production system (Fig. 9.3).

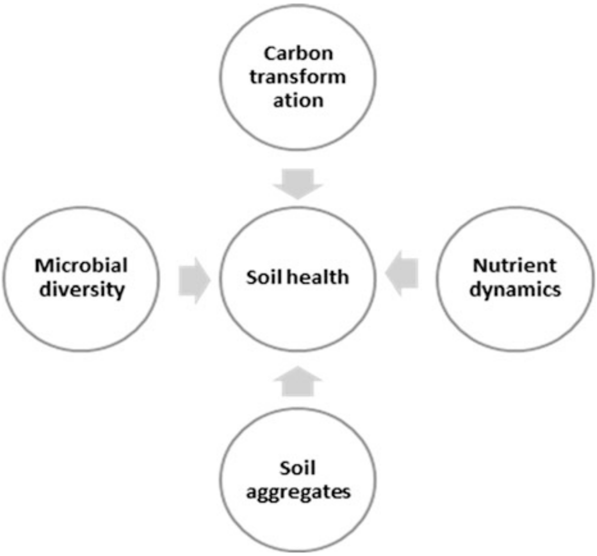

Fig. 9.2 Soil health attributes for better ecosystem performance

9.4 Soil Properties

Soil can be considered fertile when its physical makeup, chemical dynamics, and biological properties are conducive for the healthier growth of plants (Abbott and Murphy 2007). Unbalanced fertilization, intensive tillage operations, repeated crop cultivation, soil erosion, and luxury irrigation in agricultural systems push to worsening of soil health (Wander 2004; Diacono et al. 2012; Liang et al. 2013). Therefore, it is necessary to sustain soil health through best management practices and resource conservation strategies.

9.4.1 Physical Properties

Physical features of soil play a key determinant role for viable soil management and agricultural farming. Physical properties have immense effects on soil chemical reactions and biological functions, and thus nutrient dynamics in soil–plant systems. Soil as a medium of plant growth, its physical properties like soil texture, structure, compaction, density, hydraulic characteristics, etc. ensure the supporting capability of the soil, ease of root penetration, thermal diffusion, airflow, water and nutrient dynamics for better growth, and yields of crops.

9.4.1.1 Soil Texture

It is considered as one of the most prominent physical qualities due to its versatile imperious effects on numerous soil functions. In a brief, soil environment is closely interlinked with soil texture. It refers to the comparative percentage of the distinct

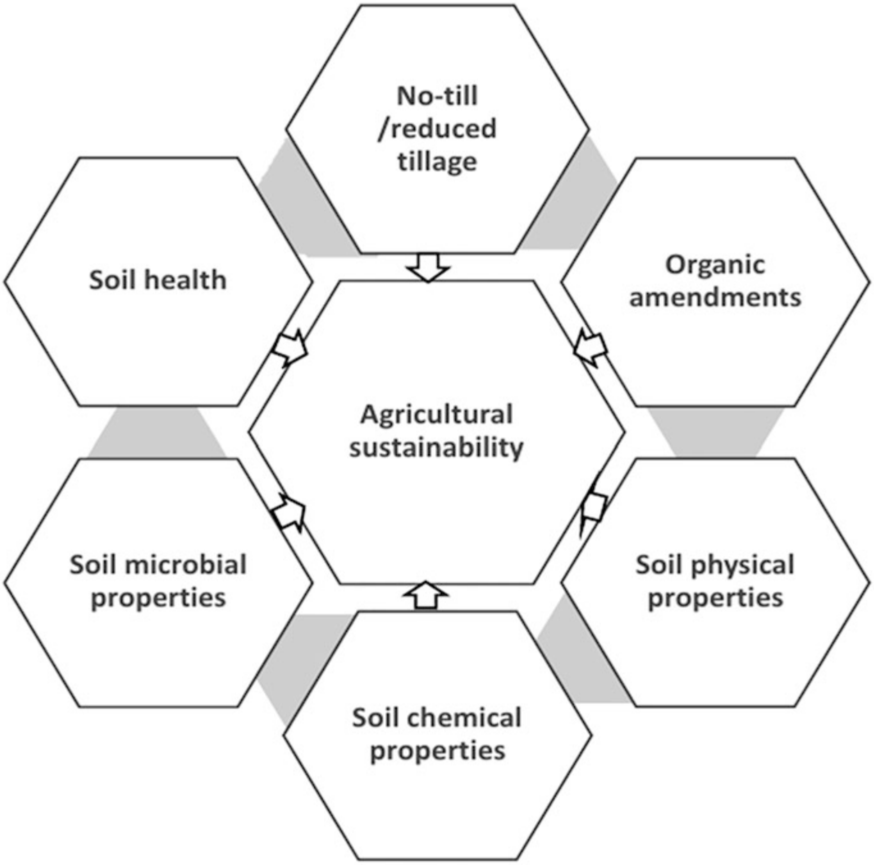

Fig. 9.3 Schematic illustration of roles of tillage and organic amendments on soil properties and agricultural sustainability

size range of soil mineral particles such as sand, silt, and clay. Minerals having 2 mm (millimetre) and/or <2 mm in size is called soil particle. Particle size over 2 mm although may have a slight impact on water retention associated properties but not included in soil texture. Soil texture is a static and inherent soil property derived from the weathered rocks and minerals that cannot be changed easily by adopting different farming practices. Soil texture is considered as the leading factor for proper soil management and determining land use capability.

9.4.1.2 Soil Structure and Aggregates

It is considered as a major functioning aspect that regulates solute, liquid, gaseous and heat flows, root penetration, and nutrient holding capacity of soils. Formation of soil structure is an interactive process of environment, soil–plant management, soil texture, OM, microbial activities, different forms of nutrient reserves, and moisture availability in soils (Kay 1998). A group of soil separates fix together to make a larger structural unit of soil aggregate, which is usually termed as a secondary particle. When such aggregation happened in the natural condition with a relatively stable form is called peds, whereas loose, irregular shaped coherent soil mass formed during tillage operation is called a clod. Thus, soil structure and aggregate are subjected to the spatio-temporal association of soil particles and pore spaces due to natural processes and anthropogenic activities of soil and crop management practices.

Soil aggregate stability states the capacity of aggregates to resists against externally imposed disruptive forces like rain flash, surface runoff, and erosion. It is a strong factor for sustaining soil physical health, which greatly affects various soil properties like improvement of porosity enhances the suitability of gas exchange, water holding capacity (WHC), and microbial activities of soil (Diacono and Mantemurro 2010). Soil with vegetation, higher clay, and OM content provides higher aggregate stability. Conservation agriculture with surface residue retention promotes soil aggregation and sustainable soil health. Disruption of aggregate stability guides to surface sealing and crust formation, which decreases the vertical entry of water through the soil profile and increase erosion risk and soil loss through runoff (Franzluebbers 2002). Higher siltation and low OM accelerate the aggregate breakdown and crusting formation (Ramos et al. 2003).

9.4.1.3 Soil Compaction and Density

Soil structural degradation due to externally or internally applied pressure is termed as soil compaction. Compaction reduces macro-pores and increases dry mass in per unit volume of soil, and thereby increases the soil bulk density. It adversely affects numerous physicochemical properties and microbial functions of soil (Whalley et al. 1995). Compaction is a complex interlinked process of soil, crops, weather, and imposed pressure. Sometimes compaction creates an impermeable layer that restricts water movement and nutrient cycling in the soil system. Some key indicators, e.g. soil pores (macro and micro), sizes of pores, bulk density, consistency and penetration capability of roots quantify the soil compaction (Hiel et al. 2016). The degree of compaction depends on the types and nature of clay, exchangeable cations, water content, and applied energy and soil management.

Bulk density is an important property for computing weight of soil considering the depth of interest. The bulk density is always lower than the particle density. In an ideal porosity (50% volume), bulk density of soil ranges from 1.30 to 1.35 g cc^{-1} (grams per cubic centimetre). In the case of coarse-textured soil, it varies from 1.40 to 1.75 g cc^{-1}, while in fine-textured one ranges from 1.10 to 1.40 g cc^{-1} (Phogat et al. 2015). Soil bulk density varied according to the soil texture, structure, moisture, OM content, and management practices. The lower bulk density indicates the higher OM and clay content of the soil. Different management practices like irrigation management, C sequestration, and nutrient dynamics depends upon the bulk density of soil.

9.4.1.4 Soil Hydraulic Properties

The soil permeability is a measure of the capacity or ease of soil to allow fluids to pass through it. Soil permeability is a very important feature to determine the movement and retention of water, nutrients, and air in the soil. It is affected by particle size, water content, void ratio, degree of saturation entrapped air, organic amendments, and tillage practices. Application of organic amendments makes soil porous and permeable, while intensive and more tillage make soil compacted and impermeable.

Soil water-holding capacity (WHC) depends on soil and crop management practices. Maximum WHC of soil is reached in field capacity when the soil contains more OM. Many soil physical characteristics like porosity, pore numbers, resistance potential, the specific surface areas, crust formation, shrinkage, and swelling ability are closely linked with the WHC of a soil. Climatic factors (rainfall and temperature), OM, texture, and structure play a major role in WHC of soil. Infiltration and evaporation are the most dominant processes that regulate WHC of soils.

Infiltration refers to the process of the downward entrance of water into the soil through the topsoil. It is the first phase that allows the transmission of water into different horizons through the soil profile. It permits the soil to provisionally stock water and keeps available for the usage of plants and microorganisms. An ample amount of water must pass through the soil profile for growth and development of plants is necessary. Gravity and soil water tension or soil matric potential control flow of soil water, which is guided by soil types and crop cultivation practices. When the amount of rainwater is more than the infiltration rate, water accumulates on soil and runoff begins.

Hydraulic conductivity accredits the easiness of water movement via the pore space. It is a computable measurement of the ability of saturated soil to transfer water. Water transmits ability through soil is controlled by the soil pores and their size and geometry (Connolly 1998). Saturated soil hydraulic conductivity is influenced by texture, clay, OM, soil aggregation, bioturbation, shrinkage, swelling and aggregate stability (Lim et al. 2016).

9.4.2 Biological Properties

Soil biology comprises the functions of flora (bacteria, archaea, and fungi) and fauna (protozoa, mites, nematodes, and earthworms). The relationship between these organisms and soil characteristics is incredibly vital on the way to maintain soil health for better agricultural production. It is well known that micro-organisms mineralize different organic materials, thus nutrients become available for crops and microbial immobilization. The nutrients immobilized by organisms restrict the nutrient loss and upon the death of microbes and subsequent mineralization, nutrients are added to the soil. Activities of soil organisms are largely responsible for improving physical and chemical properties, e.g. aeration, pH, SOM, and nutrient dynamics. Similarly, the activity of earthworm increases the infiltration rate, while the microbial activity decreases the content of SOM due to mineralization. Soil biological property can change the whole soil environment by increasing or decreasing the concentrations of nutrients through the decomposition of OM.

9.4.2.1 Nutrient Cycling

Soil microorganisms exert significant influence in controlling the quantities of different nutrients and elements in the soil like C, N, sulphur (S), and P. The mineralization of bio-degradable substances is carried out by the soil microbes that release available inorganic forms of plant nutrients including nitrate (NO_3^-), ammonium (NH_4^+), sulphate (SO_4^{-2}), etc. (Rani et al. 2019; Meena et al. 2018; Kumar et al. 2020). Assimilation of these inorganic nutrients by soil organisms and transformation into organic compounds is termed as immobilization. Microbes are the keys for the remobilization of these nutrients. Nutrient cycling is done as a result of activities of different soil organisms like bacteria (*Bacillus, Pseudomonas, Cellulomonas, Vibrio,* and *Achromobacter)*, fungi *(Aspergillus, Penicillium,* and *Trichoderma).* Protozoa, nematodes, earthworms, mites, soil insects, etc. Nitrification is a process of converting the NH_4^+ form of N to nitrite (NO_2^-) and then to NO_3^-, which is mediated by *Nitrosomonas* and *Nitrobacter*, respectively.

9.4.2.2 Biological Nitrogen Fixation

The atmosphere contains about 78% N_2 (volume basis), which is practically unavailable for the plant uptake. But some microorganisms (especially, bacteria and cyanobacteria) can capture and convert the atmospheric dinitrogen (N_2) as plant-available forms, the process is termed as biological nitrogen fixation (BNF) (Jangir et al. 2016). The BNF is accomplished by free-living bacteria (*Azotobacter, Beijerinckia, Clostridium,* etc.) or by symbiotic bacteria (*Rhizobium, Bradyrhizobium,* etc. with leguminous plants, and Azospirillum species with non-legume plants). Blue-green algae (*Anabaena, Nostoc, Cylindrospermum, Scytonema, Calothrix, Anabaenopsis, Mastigocladus, Fishcherella, Tolypothrix, Aulosira, Stigonema,* etc.) also fix the atmospheric N_2.

9.4.2.3 Plant Growth Promotion

Use of inorganic fertilizers and pesticides in agriculture has increased dramatically to produce more food for the growing population. Increased use of agrochemicals results reduced biodiversity, ill soil health, and degraded environment (Hole et al. 2005; Aktar et al. 2009). Plant growth-promoting microbes (PGPM) comprise rhizobacteria (PGPR) and fungi (PGPF) that might play vital roles to ensure agricultural and environmental sustainability. The PGPM regulates the plant growth promotion through several processes including BNF, solubilization of inorganic fixed phosphorus, production of siderophore, phytohormone and antibiotic, biocontrol of the disease-causing pathogens, nutrient uptake, etc. The important PGPR includes *Rhizobium, Pseudomonas*, *Azospirillum*, *Azotobacter*, *Erwinia, Enterobacter*, *Flavobacterium, Klebsiella*, *Alcaligenes*, *Bacillus*, *Arthrobacter*, *Burkholderia,* and *Serratia*. The species of *Aspergillus*, *Phoma*, *Fusarium*, *Trichoderma*, *Penicillium*, and arbuscular mycorrhizal fungi (AMF) are the most important PGPF.

9.4.2.4 Bioremediation

Industrial effluent discharge is an immoral anthropogenic activity that degrades soil health, air, and water quality. With the rapid urbanization and industrialization, there has been a considerable increase in the discharge of different types of wastewater to the environment. A good number of technologies have been established to handle the waste materials derived from various sources. The technological processes mainly include physical remediation, chemical remediation, phytoremediation, and microbial remediation. Many of the toxic elements embedded in waste materials could be degraded through bacterial and fungal metabolisms. The genera of *Bacillus, Streptomyces, Pseudomonas, Thiobacillus, Achromobacter, Acinetobacter, Nitrobacter, Alcaligenes, Flavobacterium,* and *Micrococcus* are important bacterial community participating in the bioremediation process of waste materials. Among the fungi, *Fusarium, Penicillium*, *Mucor, Pleurotus*, *Aspergillus*, *Trichoderma,* white rot mushrooms, AMF are recognized as efficient agents for bioremediation.

9.4.3 Chemical Properties

Soil is an environmental hub, where inherent compounds or elements and added inputs like fertilizers, pesticides undergo through a series of chemical transformation. Thus, nutrients are released to soil solution as available forms, which plants can absorb. Soil chemistry plays a pivotal role in nutrient dynamics in soil and crop productivity. All of the concepts of the soil ecology are largely controlled by its chemistry. The chemical phenomenon of soils includes nutrient elements and their compounds, OM, colloidal properties, soil reactions (pH), cation exchange capacity (CEC), buffering activity, etc.

9.4.3.1 Nutrient Elements

Solid fraction of soil is constituted by mineral and OM, which have a significant role on the source and availability of nutrient elements. Both primary and secondary minerals of the soil are the reservoir of nutrient elements. Feldspar, micas, illite are the main source of potassium (K) in soil. They also release a significant amount of calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), silicon (Si), copper (Cu), manganese (Mn), and several micronutrients. Amphiboles and pyroxene are the vital sinks of Mg, Fe, Ca, Si, and several other micronutrients. Phosphorus is released in soil from mineral apatite. Nitrogen comes in soil from organic sources such as protein, peptides, and amino acid. Nutrient elements are release in soil solution from the minerals through physical, chemical, and biological weathering process. All higher plants require 17 essential nutrient elements for completion of their life spans and metabolism (Havlin et al. 2005). Among which nine included as macronutrients (C, hydrogen (H), oxygen (O), N, P, K, Ca, Mg, and S) and rest eight comprised as micronutrients (chlorine (Cl), Fe, boron (B), zinc (Zn), Cu, molybdenum (Mo), and nickel (Ni). Additional four elements (Si, Na, cobalt (Co), and vanadium (Va), whose specific functions are not confirmed yet but their presence provide better yields in some plants. The structural elements C, H, O come from atmosphere and soil water, while all other elements derive from the soil as mineral nutrients (Parikh and James 2012).

9.4.3.2 Soil Organic Matter

Soil organic fractions consist of various stages of decomposed plant or animal tissue, microbial cells and tissues. Soil OM regulates the functions and quality of the soil. Soil OM governs all of its properties, and thus supports soil functions (Brady and Weil 1999). It provides numerous beneficial functions in the soil ecosystem. It improves soil aggregates, conserves water, increases biodiversity, reduces soil compaction, increases infiltration rate, buffering capacity, and nutrient dynamics. Soil organic matter improves soil fertility by providing exchangeable sites and acts as a major source of plant nutrients especially N, P, and S (Jangir et al. 2019). Soil OM is a major source and sink of OC and essence of soils. Fertility status of soil largely depends on OM content, while it acts as a revolving nutrient fund. Through the biochemical transformation and successive decomposition of OM, different nutrients are released to soil and finally the most reactive and stable product humus is derived. Humus is a colloidal particle, which plays an enormous role in the CEC and soil fertility. Peat is developed from un-decomposed plant tissue, while highly decomposed OM is known as muck. Soil OM contents in most of the topsoils range from 1 to 5%, which, however, decreases because of intensive agriculture with higher inorganic fertilizers and smaller amount or no organic fertilizer (Rahman et al. 2016; FRG 2018).

9.4.3.3 Soil Colloidal Properties

The most active part of the soil is its colloids, which takes part as a determinant of numerous physicochemical features. Soil consists of two types of colloids viz., inorganic (clay) and organic (humus). Predominantly most colloidal particles are negatively charged and these are active sites for chemical reactions and CEC of soil. The clay fractions of soil contain both non-colloidal and colloidal particles. Generally, clay minerals are hydrous aluminosilicates along with a noticeable amount of Fe, Ca, Mg, and Na. Clay colloid has higher water absorption and nutrient holding capacity, while humus has higher nutrient adsorptive capacity than clay colloids. Soil inherits clay colloid, while humus contents depend on soil and crop management activities. Conservation tillage coupled with residue retention and organic fertilizer addition increases humus colloid in soils.

9.4.3.4 Cation and Anion Exchange Capacity

The CEC of a soil is the measure of readily interchangeable cations that neutralize anions in the soil. It is the sum of total cations in the soil adsorption site. Soil colloidal particles clay and humus are negatively charged, which are developed during the soil formation process. They can attract or hold positively charged particles or cations. Replacement of one cation by another cation is termed as cation exchange, which makes soils capable of holding nutrients and preventing loss. The more CEC of a soil indicates the higher fertility level. Exchangeable cations in the soil maintain equilibrium between the exchange sites and soil solution (Osman

2013). The CEC varies with the type and size of ion, valance, concentration, and degree of hydration. The cation exchange in the exchange sites of a soil maintains the following order: Al^{3+} (aluminium) > H^+ > Ca^{2+} > Mg^{2+} > NH_4^+ > K^+ > Na^+. The texture, OM, clay type, and pH of soils affect the CEC. Clay soil has higher CEC than the sandy soil and 2:1 type clay mineral has higher CEC than that of 1:1 type clay mineral.

Like cation exchange, soil also shows anion exchange capacity (AEC). Replacement of adsorbed anions such as SO_4^{-2}, NO_3^-, Cl^-, HCO_3^- (bicarbonate), and $H_2PO_4^-$ (phosphate) by suitable anion is termed as anion exchange. The AEC in the exchangeable site maintains the relative order: OH^- (hydroxide) > $H_2PO_4^-$ > SO_4^{-2} > NO_3^- > Cl^- > HCO_3^-. Soil colloidal site is the place, where the anion exchange happened. Measurement of AEC is very important for proper management of problem soils such as acidic, saline and or alkaline soil.

9.4.3.5 Soil pH

Soil reaction or pH is termed as a master variable of chemistry due to its manifold impacts on soil properties (Hillel and Hatfield 2005). Acidity and alkalinity of soil are defined based on H^+ concentration in soil solution. Soil nutrient release, nutrient uptake, ionic toxicity, and microbial mobility are remarkably inclined to soil pH (Heggelund et al. 2014). The pH of agricultural soil ranges 6.0–7.5, which indicates that slightly acidic, neutral and slightly alkaline conditions are good for optimal nutrient availability, and thereby crop productivity. The solubility of macronutrients (N, P, K, Ca, Mg, S) plus Mo is restricted at low pH. In contrast, micronutrient availability (Cl, Fe, Zn, Cu) minus Mo is higher in low pH. Soil pH either lower (<5.5) or higher (>8.5) poses a great threat to global crop productivity due to providing a nutrient imbalance and ionic toxic atmosphere for the plant. Soil parent materials, weathering reaction, rainfall, irrigation water quality, OM, vegetation, and fertilization are considered as the major sources of variation of soil pH (Heggenstaller 2012).

9.4.3.6 Buffering Capacity

Acidification and alkalization pose a great threat to sustainable soil management and agricultural productivity. The extreme variation in soil pH can be minimized by increasing the buffering capacity of soils. The capacity of soil to neutralize pH change is termed as the buffering capacity of the soil. Organic matter and clay contents are the major agents responsible for such safeguarding capacity (Magdoff et al. 1987). Protonation and de-protonation of buffering agents reduce the pH change. Dissolution of aluminosilicate at low pH is considered as acid buffer mechanism, while at high pH calcium carbonate ($CaCO_3$) dissolution activates the buffering capacity of soils. Exchangeable sites of minerals and OM take part in buffering activity, as they are the source and sink of H^+ and OH^- ions. Organic matter displays buffering activity by releasing weak carboxylic and phenolic group, while such buffering depends on soil C contents and tillage practices (Weaver et al. 2004).

9.5 Effects of Amendments on Soil Properties

Organic amendments are a good source of nutrients, which further can improve soil aggregates, enhance nutrient dynamics, harbour microbial diversity and their activity (Antonious 2016). Organic amendments contain a significant amount of C, N, P, and K (Table 9.2). Application of such amendments to crop fields ensures the best use of available natural resources, which slowly release different nutrients to the soil and thus improve soil environment and reduce the requirement of inorganic fertilizers for crop production (Wilhelm et al. 2007).

Retention of crop residues in fields is an important resource conservation strategy, which enhances the physicochemical as well as biological parameters of soil health improvement. In several Asian countries, more especially in the south Asian region, crop residues are utilizing for different purposes such as fuel for cooking, animal fodder, and housing for the animal, fencing, etc. In the intensive production system, farmers remove crop residues from the harvested fields so that the fields become clear and suitable for the growing of next crop. Even the farmers burn the crop residues. However, the crop residue is a large source of OM that replenishes OC and nutrients in soils. Retention of crop residues in crop fields of Asia, Latin America, and Africa revealed that it improves soil quality, increases SOM and C stock, soil moisture content, improves nutrient transformation and decreased soil erosion (Turmel et al. 2015).

Soil is overwhelmingly the greatest natural resource, which is degraded as a result of various anthropogenic and natural activities all over the world. Depletion of soil fertility is considered as one of the vital factors that restrict increased crop production to feed the increasing population. Greater dependency on chemical fertilizers and

Table 9.2 Organic carbon, nitrogen, phosphorus, and potassium contents of different organic amendments

Amendment/manure	OC (%)	N (%)	P (%)	K (%)	References
Rice straw	–	0.5–0.8	0.07–0.12	1.16–1.66	Dobermann and Fairhurst (2002)
	36.2	–	–	–	Alam et al. (2019)
Cow dung (decomposed)	–	1.00	0.30	0.46	FRG (2018)
	13.8	–	–	–	Alam et al. (2019)
Poultry manure (decomposed)	–	1.25	0.70	0.95	FRG (2018)
	8.4	–	–	–	Alam et al. (2019)
Farmyard manure	–	1.60	0.83	1.70	FRG (2018)
Compost (rural)	–	0.75	0.60	1.00	FRG (2018)
Compost (urban)	–	1.5	0.60	1.50	FRG (2018)
Vermicompost	–	1.1	0.11	0.42	Akter et al. (2017)
	12.2	–	–	–	Alam et al. (2019)
Trichocompost	–	2.42	1.26	1.42	Akter et al. (2017)
Household waste compost	–	3.32	0.61	1.59	Smith and Jasim (2009)

imbalanced nutrient management practices without replenishment of OM for intensive crop cultivation, use of high biomass producing crops (e.g. maize), utilization of high yielding crop varieties, removal of crop residues from crop fields, use of less or no organic fertilizers, lack of crop rotation, etc. have created remarkable influences on soil nutrient removal and thus led to the deterioration of soil health and fertility and impaired the productivity of soils (Rahman 2013; Kumar et al. 2017; Sharma et al. 2019). As soil fertility is considered as an essential element for better crop cultivation, therefore, the improvement of fertility status is a must for crop productivity sustainably. Crop residues, CD, PM, farmyard manure, compost, and other manures available in the farm household could be considered as a good source of manure that can be applied to soils (Channabasavanna 2003) for achieving good soil properties to facilitate profitable crop production (Somani and Totawat 1996). Therefore, it is necessary to ensure the application of organic manures in combination with inorganic fertilizers in agriculture for sustainable soil health as well as better crop production. The effects of different organic amendments on soil properties are provided in Table 9.3.

9.5.1 Rice Straw

In a sustainable agricultural system, recycling of nutrients is the key to nutrient management (King 1990). Among different types of organic materials, the availability of rice straw is considerably high in almost all agricultural farms that can be added into the soil as a source of organic manure. It has been reported that rice straw contains different nutrients such as N (0.5–0.8%), P_2O_5 (0.16–0.27%), K_2O (1.4–2.0%), S (0.05–0.1%), and Si (4–7%) (Dobermann and Fairhurst 2002). Being good source plant nutrients, rice straw addition in the soil increases the yield as compared to the burning or removal of straw (around 0.4 t ha^{-1} per season), and the yield increases gradually due to the builds up of soil fertility with time (Ponnamperuma 1984).

It is noteworthy that considerable amount of nutrients up taken by the rice plant remains in vegetative plant parts (N 40%, P 30–35%, K 80–85%, and S 40–50%) at the maturity stage of the crop (Dobermann and Fairhurst 2002). Rice straw is also considered a significant source of micronutrients like Zn and Si. In many countries of the world, it is very common to remove the straw from the harvested field, which consequences the depletion of nutrients especially K and Si from the soil. Straw is removed from the field for different purposes such as cooking, animal fodder, animal bedding, the raw material for industry (for instance, paper making), etc. It is an efficient way to return most of the plant nutrients into the soil through the incorporation of straw and stubbles, which will ensure the conservation of soil nutrient reserves in the long term. Application of synthetic chemical fertilizers along with straw incorporation, the status of soil nutrients particularly N, K, P, and Si are maintained and may even be improved. So, it is revealed that RS is the best alternative to increase OM contents and decrease the bulk density of soil as well as to

Table 9.3 Effect of organic amendments on soil properties

Amendments	Soil properties	References
Rice straw	It decreases soil bulk density by 0.12 g cc^{-1}, and increases total porosity by 4%	Wen-Wei et al. (2011); Gui-mei et al. (2015)
	Rice straw incorporation in soil increases OM content by 1.18 g kg^{-1}, while N, P and K by 25.7, 25.7, and 3.7 mg kg^{-1}, respectively	
Cow dung	Application of 10 t ha^{-1} cow dung significantly increased OM, N, P, Ca, and Mg in soil as compared to the application of NPK fertilizers	Ewulo et al. (2007)
	Soil pH increased by 6.12, 8.16, and 10.20% with the addition of CD at the rate of 5, 7.5, and 10 t ha^{-1}, respectively, as compared to the control treatment	Zaman et al. (2017a)
Poultry manure	It increases the availability of Fe, Cu, Mn, Zn, and B in soils	Ghosh et al. (2004)
	Soil OM, total N, available P, and moisture content were increased but bulk density was decreased with the application of increasing rate of PM	Ewulo et al. (2008)
	After five rice growing season, soil pH increased by 15.34% because of application of PM at the rate of 2 t C ha^{-1} $season^{-1}$ compared to the control treatment	Rahman et al. (2016)
	Soil pH increased by 8.16, 12.26, and 18.36% with the addition of CD at the rate of 5, 7.5, and 10 t ha^{-1}, respectively, as compared to the control treatment	Zaman et al. (2017b)
	Poultry manure contributed to increase macroaggregates in soil by 4–6% as compared to inorganic fertilizer treatment	Hoover et al. (2019)
Farmyard manure	Application of FYM + NPK for three consecutive years increased soil OC by 41% compared to the initial value of 4.4 g kg^{-1}	Hati et al. (2006)
	Integrated use of FYM + NPK significantly decreased soil bulk density (9.3%), soil penetration resistance (42.6%), while increased hydraulic conductivity (95.8%), water-stable aggregates (13.8%), and OC (45.2%) compared to the control	Bandyopadhyay et al. (2010)
Compost	Continuous addition of compost for 5 years increased soil C and N by 2.02 and 0.24 t ha^{-1}, respectively	Whalen et al. (2008)
	The highest bacterial population was enumerated in vermicompost amended soil (55.19×10^5 CFU g^{-1} dry soil) followed by farmyard manure (54.26×10^5 CFU g^{-1} dry soil), whereas the lowest number was recorded in the control treatment (30.89×10^5 CFU g^{-1} dry soil)	Das and Dkhar (2011)

CFU Colony forming unit

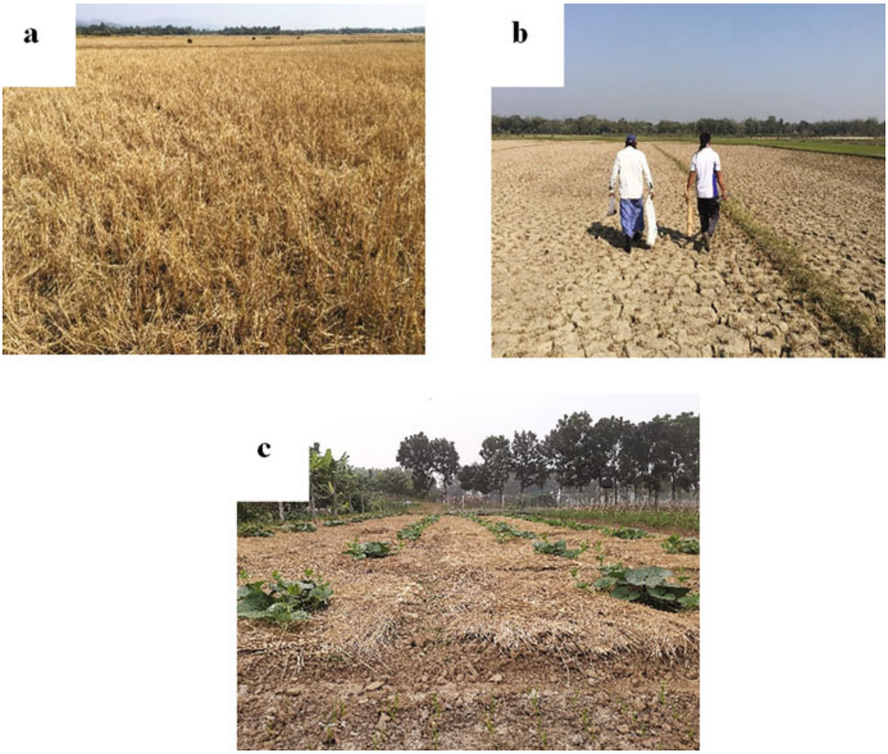

Fig. 9.4 Rice straw retention (**a**), removal (**b**), and mulch (**c**) in crop fields of Bangladesh (Photo courtesy (**a** & **b**): Dr. Alam, BARI, Bangladesh, and (**c**) Prof. Rahman, BSMRAU, Bangladesh)

sustain soil fertility (Table 9.3). Figure 9.4 shows RS retention (Fig. 9.4a), removal (Fig. 9.4b), and mulch (Fig. 9.4c) in different locations of Bangladesh.

Rice straw is considered as a vital source that improves the fertility status of soil by increasing organic matter content and improving soil moisture condition (Ruensuk et al. 2008). Moreover, incorporation of rice straw consequences better soil nutrient status increases soil biological activities, as well as soil fertility. It has been demonstrated that RS incorporation in soil could effectively improve the soil fertility and increase the OM content by 1.18 g kg^{-1} and N, P, and K by 25.7, 25.7, and 3.7 mg kg^{-1}, respectively (Gui-mei et al. 2015). Rice straw addition could also improve the physical properties of the soil. Rice straw significantly improved soil physical properties by reducing the soil bulk density by 0.12 g cc^{-1}, increasing total porosity and ventilation porosity by 4 and 6.8%, respectively (Wen-Wei et al. 2011).

Binte (2020) reported from a 5 years long field experiment that rice straw addition increases the porosity and decreases the bulk density of soil (Fig. 9.5). A long-term ongoing study using rice straw and other organic materials, which commenced in 1988 at BSMRAU research field of Bangladesh reveals that soil physicochemical properties greatly improves due to the addition of organic materials as compared to

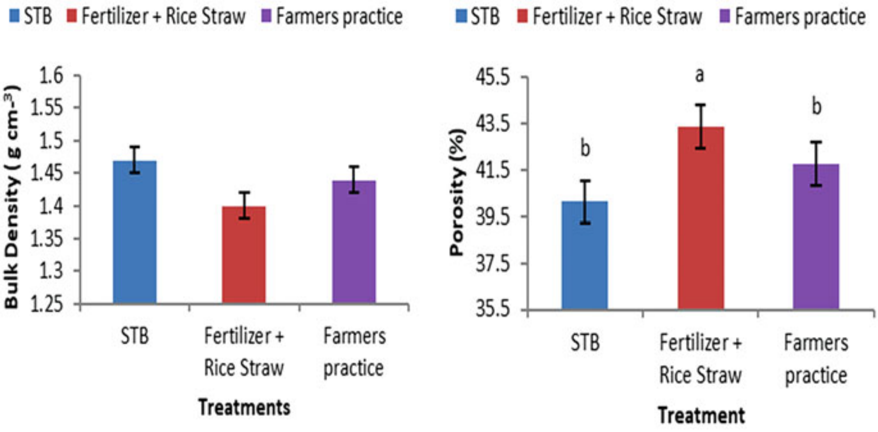

Fig. 9.5 Effects of rice straw on bulk density and porosity of soil (Adapted, Binte 2020)

Table 9.4 Effect of seasonal application of NPK and different organic fertilizers on soil (0–15 cm) chemical properties after 30 years (1988–2017) of cultivation (Unpublished data)

Treatments	Bd (g cc^{-1})	AS (%)	OC (%)	pH	CEC (cmol kg^{-1})	P (mg kg^{-1})
NPK	1.43	43.2	0.77	5.5	99.9	10.1
CD	1.38	55.9	1.14	5.8	119.8	17.5
CP	1.37	56.1	1.15	5.7	132.1	16.8
GM	1.39	53.8	1.08	5.7	135.0	17.2
RS	1.41	55.2	1.12	5.7	127.0	17.6
Control	1.45	42.1	0.84	5.5	94.6	7.7
LSD	0.03	3.75	0.24	0.3	13.96	2.84
CV (%)	1.2	4.0	12.7	2.9	6.5	10.7

CD cow dung, *CP* compost, *GM* green manure, *RS* rice straw, *Bd* bulk density, *AS* aggregates stability of 0.25 mm sized soils, *CEC* cation exchange capacity, *cmol kg^{-1}* centimole per kilogram, *mg kg^{-1}* milligrams per kilogram, different letters indicate significant differences among the values within a column

the sole inorganic fertilizer (NPK) and the control treatments in rice-wheat cropping pattern (Table 9.4). Data presented in Table 9.4 reveals that RS increases soil aggregate stability, OC, CEC, and P by 27.8, 45.5, 27.2, and 74.7%, respectively, compared to only inorganic fertilizer treatment.

Soil microbes play a crucial role in maintaining the soil fertility through participating in various soil processes including nutrient cycling, N fixation, and nitrification process. Better soil microbial diversity is considered as an indicator of healthy soil (Watts et al. 2010; Tautges et al. 2016). It has been demonstrated that addition of RS in the soil increases the number of microbes especially bacteria, actinomycetes, and bacteria/fungi more than two-fold, while the fungal population decreased approximately by 50% (Zhang et al. 2018). Moreover, RS addition had positive effects on soil OC, dehydrogenase activity, microbial biomass C as well as diversity (Goyal et al. 2009; Zhang et al. 2018). Straw is rich in readily available C (Zhang et al. 2018) which might be utilized by the microbes as an energy source. Therefore, straw incorporation enhances the microbial population in the soil.

9.5.2 Cow Dung

The application of organic manures including different animal manures in the soil is the prime need for maintaining soil fertility status for sustainable agriculture. Cow dung is an important resource that has tremendous beneficial effects for improving the soil properties. Cow dung is a traditional source of crop nutrients all over the world more specifically in the Asian and African countries, which not only increase the crop production but also ensure better soil quality. It is a mixture of faeces and urine of herbivorous bovine animals, which consist of lignin, cellulose, and hemicelluloses as major components. It contains most of the plant nutrients, for example, N, P, S, Fe, Mg, Cu, Co, and Mn (Gupta et al. 2016). It has been demonstrated that the CD derived from indigenous Indian cow contains a higher amount of P, Ca, Zn, and Cu compared to the cross-breed cow manure (Randhawa and Kullar 2011).

Experimental results indicated that application of CD in combination with NPK fertilizer improved soil organic matter, available phosphorus, exchangeable cations, CEC and base saturation (Stanley 2010). Application of CD increases soil pH, OM, N, P, Ca, and Mg contents in soil (Table 9.3). Results also show that the application of CD increases porosity, moisture content, and decreases the bulk density, temperature, and dispersion ratio of soil compared to no manure application (Adekiya et al. 2016). Hydraulic conductivity and aggregate stability could also be increased significantly with the application of CD in soil (Nweke and Nsoanya 2015). It has been reported that CD increases soil aggregate stability, OC, CEC, and P by 29.4, 48.1, 20.0, and 74.0%, respectively, compared to only inorganic fertilizer treatment (Table 9.4). Addition of CD considerably improved soil respiration indicating higher microbial activity (Adebola et al. 2017; Meena et al. 2020c). Cow dung addition also increased the microbial biomass C. This suggests that OC derived from CD were utilized by the soil microorganisms and thus promotes the microbial growth.

Cow dung harbours a greater extent of microbial diversity including different species of bacteria and fungi. Experimental results demonstrated broad ranges of microorganisms in CD such as *Bacillus*, *Acinetobacter*, *Serratia, Pseudomonas*, and *Alcaligenes* spp., which are very effective to improve the polluted soils through the degradation of pollutants (Adebusoye et al. 2007; Umanu et al. 2013). Furthermore, bacterial isolates such as *Bacillus*, *Pseudomonas*, *Citrobacter*, *Vibrio*, *Micrococcus*, *Flavobacterium,* etc., and fungal isolates such as *Aspergillus*, *Fusarium*, *Rhizopus*, *Penicillium*, *Mucor,* etc. isolated from CD dramatically improved the petroleum polluted mangrove soil (Orji et al. 2012). Hence, the CD might play a vital role in the improvement of polluted soils. It implies that CD is a valuable natural resource that can significantly improve soil properties. A significant portion of the produced dung is not added to the soil due to use in other purposes like burning for cooking purpose. However, the scenario might be changed through increasing awareness of the rural farmers regarding the importance of soil health as well as providing alternate fuel source to the rural women.

9.5.3 Poultry Manure

Poultry manure is also a vital organic fertilizer that has been using traditionally in crop field for maintaining soil fertility and better crop production all over the world. This manure is originated mainly from the faeces along with urine and bedding material of the poultry birds (Rahman et al. 2020). Globally, the poultry sector is growing rapidly to fulfil the increasing requirement of the growing population. Therefore, a huge quantity of poultry litter is generated every year from a large number of poultry birds. Poultry litter may cause health and environmental hazards due to the lacking of proper management techniques. Utilization of the poultry litter as organic manure in agriculture is profitable as well as environmentally friendly.

Poultry manure is a good source of OM that contains a substantial amount of primary essential nutrients like 1.25% N, 0.7% P, and 0.95% K (FRG 2018), and other essential plant nutrients that are highly available for plant utilization in comparison with other organic fertilizers (Garg and Bahla 2008; Mohamed et al. 2010). Information provided in Table 9.3 revealed that PM could increase the availability of micronutrients Fe, Cu, Mn, Zn, and B, and soil pH (Ghosh et al. 2004; Rahman et al. 2016), and soil macroaggregates by 4–6% as compared to inorganic fertilizer treatment (Hoover et al. 2019). Availability of nutrients in the soil is largely dependent on soil pH. It has been demonstrated that pH value varying from 5.5 to 7.0 is comparatively satisfactory for the availability of most of the plant nutrients (Brady and Weil 2014). Long-term application of inorganic fertilizers decreases the pH value in comparison with the combined application of organic manures and inorganic fertilizers (Ge et al. 2018). On the contrary, PM has a liming effect as it increases the soil pH (Mullens et al. 2002; Rahman et al. 2016), which might be due to the presence of a significant amount of liming materials like $CaCO_3$ in poultry feed. Therefore, in acid soil, PM is a good source of organic manure for the correction of soil acidity as well as to improve the fertility status of the soil.

Poultry manure contributes a significant amount of OC in the soil, thus improve the soil properties through the improvement of soil structure, aggregate stability, WHC, soil aeration, buffering against sudden change of the soil pH, CEC as well as soil microbial activities (Bauer and Black 1992). Organic matter that derived from various sources of organic materials is a rich pool of supplying essential plant nutrients to the soil (FAO 2005). Nutrient availability in soil is basically reliant on its better physicochemical and biological properties. Application of PM enhances chemical properties of soil, for example, it increases OC, N, K, P, Mg, and Ca contents in soil (Agbede et al. 2008; Soremi et al. 2017). Similarly, physical properties of soil were improved with the addition of PM in the soil, for instance, it reduces bulk density, increases porosity & moisture status of soil, decreases soil temperature (Ewulo et al. 2008; Agbede et al. 2008), increases infiltration rate at clay loam soil, while decreases the infiltration rate at sandy clay loam textured soil (Adeyemo et al. 2019). Poultry manure not only improves the physicochemical properties but also contributes to soil biological characteristics. Research findings documented that application of PM as organic waste increases microbial biomass, enzyme activities, and microbial quotients in soil (Kaur et al. 2005; Tejada et al. 2006). Poultry manure increases the bacterial population in the soil, which may enhance the fertility status of soil (Maguire et al. 2006). Bacterial diversity based on species richness and evenness was considerably better in soils that received PM in comparison with the sole application of inorganic fertilizers (Jangid et al. 2008). Therefore, the addition of PM in the soil as an organic fertilizer has great potentialities to enhance the fertility status of soil through the improvement of soil biological as well as physical and chemical properties.

9.5.4 Farmyard Manure

It is one of the important as well as older organic manures applied by the farmers traditionally to the agricultural fields to grow crops especially the horticultural crops due to its higher availability and nutrient supply ability to the crops. Farmyard manure comprises the solid and liquid animal excreta (animal dung and urine), the residual part of the animal fodder and the used bedding material of the animals (Rahman et al. 2020). As organic manure, FYM has the great potentialities to provide all essential primary and secondary plant nutrients, i.e., N, K, P, Mg, Ca, and S as well as some essential micronutrients like Mn, Cu, Fe, and Zn (Meena et al. 2018). Amendment of FYM in the soil increases its nutrient status (N, P, K) (Meena et al. 2018), and therefore, fertility status of the soil improves. The SOC indicates the soil quality, which is directly associated with cycling plant nutrients and improvement of soil properties. Addition of FYM along with a recommended dose of synthetic NPK fertilizers (NPK + FYM) for three successive years improved the soil OC content from the original value of 4.4 g kg^{-1} to 6.2 g kg^{-1} (Hati et al. 2006). Soil OC content directly administers the structural stability of the soil. Soil amendments with FYM manure ensure the improvement of OM, pH, and hydraulic conductivity that provides a better soil environment (Table 9.3).

Sole amendment of FYM in soil or amended with synthetic fertilizers ensure a higher percentage of water-stable aggregates enhanced saturated hydraulic conductivity, improved soil porosity, decreased soil bulk density and soil penetration resistance (Hati et al. 2006; Bandyopadhyay et al. 2010; Meena et al. 2018). Increased porosity of the surface layer of the soil provides better aeration and thereby promotes healthier root growth in soil. Addition of FYM also favour the physical properties of problem soils, for instance, bulk density, porosity, void ratio, water permeability, and hydraulic conductivity of a saline-sodic soil was considerably improved when farmyard manure at a rate of 10 t ha^{-1} was added in conjunction with chemical amendments (Hussain et al. 2001). Soil amendment with FYM improves the soil biological properties as FYM provide a higher amount of OC, which favour increased microbial activity. Experimental results reveal that application of FYM significantly increases microbial biomass, dehydrogenase activity, earthworm community composition, and earthworm cast production in the soil as compared to the soil that received no FYM (Zaller and Kopke 2004).

9.5.5 Compost

Compost is ecologically sound organic manure that improves soil quality as well as reduces the environmental hazards arising from different waste materials generated in both rural and urban areas. Compost is prepared through the decomposition of different organic residues including household waste materials, any plant residues, animal waste, wood waste, industrial waste, municipal waste, etc. Waste materials should be selected carefully for the preparation of compost so that toxic elements remain below the allowable limits. Application of compost in soil favourably enhances the physicochemical as well as biological properties of soil (Table 9.3). Compost application significantly increases the amount of soil OC (Whalen et al. 2008), which directly enhances the soil properties. Organic matter ensures better soil structure through its binding effect as well as enhanced root development and biological activity (Farrell and Jones 2009; Gao et al. 2010). Compost derived from various sources improves soil water retention ability, thus increasing the availability of water to the plants (Farrell and Jones 2009). Results obtained from a field experiment demonstrated 58–86% increase of available soil water content due to the application of cattle manure compost (Celik et al. 2004), which might be due to the improvement of macro and microporosity of the soil. Therefore, the application of organic manure, especially the composted manure in arid and semi-arid areas could be vital to conserve water over the crop growing season. Moreover, compost application could improve the drainage capacity, aeration, and aggregate stability of soil (Avnimelech et al. 1990; Duong et al. 2012). Compost application significantly alters the bulk density of soil. Soil bulk density decreases gradually by the application of an increasing amount of compost (Brown and Cotton 2011). Lower soil bulk density might be due to the increased pore space, which indicates the improvement in soil tilth.

Compost not only provide a considerable amount of plant nutrients but also decreases the leaching loss of nutrients (Hepperly et al. 2009), reduces erosion, and evaporation. Soil amendments of compost appreciably increase the nutrient status of soil, even after several years of application (Butler et al. 2008). Compost increases soil pH, aggregate stability, OC, and P by 13, 29.9, 49.4, 32.2, and 66.5%, respectively, and decreases soil bulk density by 13.4% compared to sole fertilizer treatment (Table 9.5). Effects of compost on soil pH rely on the raw material from, which the manure has been prepared. Application of chicken litter compost results in an increase of soil pH (Hubbard et al. 2008), which might be due to the basic cations associated with the poultry feed. Decrease of soil pH was also reported with the addition of compost prepared from rice straw and waste materials derived from various agro-industries, which might be as a result of the release of different organic

Table 9.5 Tillage operations and their effects on soil properties and crop yields

Tillage	Effects on soil properties and crop yields	References
No-till	In a study of maize (*Zea mays*) and maize with soybean (*Glycine max*) in the USA it was found that no-till system reduces N_2O emission by 40, and 57% compared to moldboard and chisel plough, respectively	Omonode et al. (2011)
	About 70% of energy and fuel can be saved in the no-till system compared to TT	Friedrich and Kassam (2012)
	A 41-year study in France indicated that no-till system did not increase soil C stock	Dimassi et al. (2014)
	No-till with residue holding increased N_2O emission by 82.1% from paddy fields in China	Zhao et al. (2016)
	In a four-year study in Bangladesh, it was found that total C stock in soil increased by 28 and 27% in no-till under wheat (*Triticum aestivum*)-dhaincha (*Sesbania grandiflora*)-rice and wheat-mungbean (*Vigna radiata*)-rice, respectively	Alam et al. (2017)
Reduced tillage	In Australia, wheat yields were found 7.9 and 8.0 t ha^{-1} under RT and TT, respectively	Akbarnia et al. (2010)
	Reduced wheat yield by 67% compared to TT in Germany	Zikeli and Gruber (2017)
Strip tillage	Soil saturated hydraulic conductivity was found 23–138% higher in strip tillage compared to TT	Jabro et al. (2011)
	After 6 years of strip tillage, bacteria and fungi in soil increased by 27 and 37%, respectively compared to TT	Leskovar et al. (2016)
Ridge tillage	A 29-year study unveiled that ridge tillage contributed to higher soil C in the crests and lower in the inter-rows compared to no-till	Shi et al. (2012)
Traditional tillage	From a total of 78 studies comprising no-till and TT across the world, 40 studies showed lower C stock in TT	Govaerts et al. (2009)
	A 10-year study in Inner Mongolia indicated that soil OC, total N and Olsen P decreased by 19, 27 and 21%, respectively in TT compared to no-till with straw cover	He et al. (2009)

acids and release of H^+ during nitrification process (Bolan and Hedley 2003; Rashad et al. 2011). Cation exchange capacity is closely related to the nutrient retention capacity of the soil, and thus play a vital role in the evaluation of soil fertility. The higher CEC prevents the leaching loss of cations into the groundwater. It has been reported that compost application increases the CEC of soil (Agegnehu et al. 2014), which might be attributed as good quality composts provide stabilized organic matter in the soil, which includes various functional groups.

Soil organisms perform a considerable role in preserving soil fertility by regulating the physicochemical properties of soil. Soil microbes like fungi, bacteria, algae, and actinomycetes demonstrate significant contribution in OM decomposition, nutrient cycling and important chemical transformations in soil (Murphy et al. 2007). Biological functioning of soil largely depends on available C content in the soil. The activities of the microbes in soil increase due to the application of composted material. Microbial activity was more than two times higher in compost applied soils as compared to the un-amended soils (Brown and Cotton 2011). Compost amendment results in higher earthworm and microbial biomass, increased mycorrhizal root colonization and higher microbial diversity in soil (Paul 2003). Long-term compost amendment improves soil biological characteristics such as several microbes, biomass C and nitrogen, soil respiration, and enzymatic activities (Chang et al. 2014). Thus, compost amendment in the soil might play an important role in improving soil fertility as well as soil health.

9.6 Tillage Practices and Soil Properties

Soil tillage is widely used traditional cultivation practice employed before sowing seeds or planting saplings. It is done to make the soil suitable for seed germination, crop production and used to mix crop residues and fertilizers in soils, and control weeds in crop fields. However, tillage impacts the soil quality through physical disruption, which brings changes in soil C and water contents, soil structure, diversity of the microbial population, and nutrient dynamics (Wang et al. 2016; He et al. 2019; Meena et al. 2020b). Traditional tillage greatly disturbs soils through more and deep ploughing, which caused for deterioration in soil quality through nutrient depletion and erosion, increasing cost of production and energy use, and contributing to greenhouse gases (GHGs) emissions (Hobbs 2007). On the other hand, conservation tillage viz. no-till, reduced tillage (RT), etc. develops soil structure, improves soil health, and sustains its quality. No-till and reduced tillage reduces GHGs emissions and C footprint of a crop and mitigates the negative effects of climate change (Van den Putte et al. 2010; He et al. 2019). Effects of different types of tillage practices on soil properties and crop yields are shown in Table 9.5.

9.6.1 No-Till/Zero Tillage

No-till or direct seeding is an approach of cultivating crops or grassland without ploughing down the soil using tillage equipment. In the no-till system of crop cultivation, seeds are sown directly into the soil, where the residue is spread over the land surface that has not been tilled (MDA 2011). The previous year's crops or residues are cut down and spread on the topsoil before sowing seeds. After spreading of crop residues on the soil surface, a no-till planter is used that slightly punctures the soil to sow seeds. The no-till cultivation system is commonly used in a big commercial farm using larger implements. Small scale farmers usually go for the no-till system by hand. Under the no-till farming system, incorporation of crop residues into the soil by tools/machinery is avoided but distributed evenly on the soil of the crop field (Kakraliya et al. 2018; Meena et al. 2018). No-till is one of the forms of CA that encompasses least soil distraction, residue mulch, and crop rotation (Campbell-Nelson 2019). Such farming is a win-win technology that reduces labour, irrigation, fuel, and machinery costs, while reduces soil erosion, increases soil C sequestration, reduces GHGs emission, improves soil health, and finally attributed to

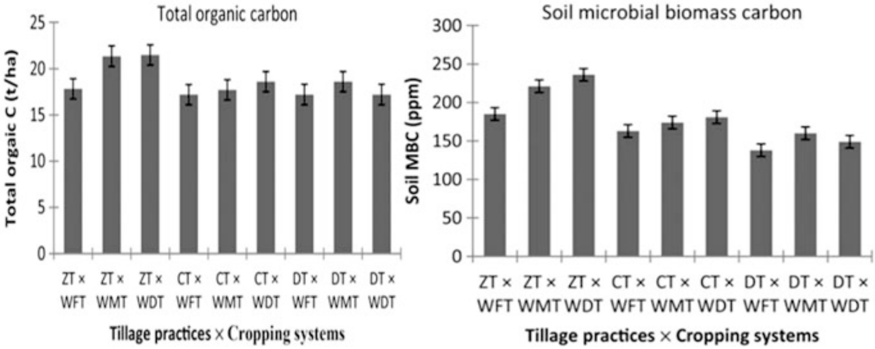

Fig. 9.6 Tillage and cropping patterns on total soil organic carbon (SOC) and microbial biomass C after 4 years of cropping (*ZT* zero tillage, *CT* conventional tillage, *DT* deep tillage, *WFT* wheat-fallow-T. aman, *WMT* wheat-mungbean-T. aman, *WDT* wheat-dhaincha-T. aman) (Adapted, Alam et al. 2017)

higher crop yields (Derpsch et al. 2010). A longer time is obligatory to get the positive results of no-till on yields of crops in wetter condition, however, in moisture limiting drier areas its effect is quick and obvious (Kimble et al. 2007).

A viable and sustainable cropping system comprises no-till, MT, crop rotation, and residue retention. Such a system increases microbial biomass, their abundance and activities in soils compared with traditional agricultural practices. After 4-years of cropping with tillage and crop rotation, Alam et al. (2017) identified a higher amount of OC and biomass C in zero tillage (Fig. 9.6). Contradiction also exists that no-till system may or may not increase C stock in soil, but it is confirmed that it reduces fuel and energy costs (Table 9.5). Adoption of no-till coupled with residue retention and cover crops makes situations promising for the progress of ecological stability and agricultural sustainability. It is stated that practising no-till or reduced tillage devoid of crop residue retention and cover crops long time may result in degraded soil with ill health that pushes the agricultural production and environment towards vulnerable conditions (Govaerts et al. 2007).

No-till alone increased soil aggregates, bulk density, C, and other nutrients in soils than that of TT, while no-till coupled with cover crops and residue retention provides further benefits to soil health management (Valpassos et al. 2001; Mitchell et al. 2017). Valpassos et al. (2001) conveyed that 8 years old no-till with continuous crop rotation with bean, corn, soybean, and dark-oat increased soil OM, biomass C, pH, and P content compared to 10-years old conventional cultivation with crop residue application and crop rotation in Brazil (Table 9.6).

It is evinced that adoption of only one novel technology would not enough to sustain the long-term agricultural production. Location-specific a set of synergistic viable technologies should be selected and recommended for better soil management and higher crop productivity. Adoption of no-till cropping system may offer a huge economic, environmental, and social benefit. Therefore, no-till technology along with other suitable technologies is gaining popularity across the globe. The area

Table 9.6 Physical, chemical, and microbial properties of soil under different management options

Soil management	Soil properties under different management				
	Bulk density ($g\ cc^{-1}$)	Organic matter ($g\ kg^{-1}$)	pH	Phosphorus ($mg\ kg^{-1}$)	Biomass C ($mg\ kg^{-1}$)
No-tillage	1.32b	42.52a	5.31	35.26a	469.14a
Cerrado	1.18d	30.57b	3.98	6.86c	347.91ab
Conventional	1.26c	24.15c	5.13	16.18a	315.47ab
Pasture	1.60a	22.86c	5.07	10.16b	213.03b

Bd bulk density, *OM* organic matter, *P* phosphorus (Adapted, Valpassos et al. 2001)

under the no-till method is increasing globally with the advancement of time. Derpsch et al. (2010) reported that the no-till farming area was 45, 75, and 111 million ha in 1999, 2003, and 2009, respectively, with a corresponding growth rate of six million ha year^{-1}. The maximum adoption rates of no-till technology have been observed in different South American countries, where some countries have been using the technology on roughly 70% of the total agricultural land (Derpsch et al. 2010). It has been reported that about 62–92% of farmers in Australia practiced no-till farming on 73–96% of their crop fields (Kirkegaard et al. 2014). Such encouraging spreading of the promising no-till practice in agriculture indicates the great compliance of the systems to all climatic and edaphic conditions of the world.

No-till practice emits generally less carbon dioxide (CO_2) due to less disturbance in soil and slower mineralization of OM and fertilizers. Jia et al. (2016) conducted a study in China using maize-corn rotation and found that overall CO_2 emissions under no-till were about 7.8% lower compared to moldboard plough. Regarding N_2O emission, such a statement is not straightforward, where denitrification is more pronounced in the no-till system compared to the tilled system. However, N_2O emission from croplands depends on different cropping systems, soil types, soil and crop management practices. Rochette (2008) stated that average nitrous oxide (N_2O) emissions from a no-till system of well-drained soil were 0.06 kg N ha^{-1} lower than that of tilled soil, while in medium and poorly drained soils were 0.12 and 2.00 kg N ha^{-1} higher, respectively. In a long-term study of maize and maize with soybean in the USA established that no-till system reduces N_2O emission by 40, and 57% compared to moldboard and chisel plough, respectively (Omonode et al. 2011). Likewise, no-till with residue holding increased N_2O emission by 82.1% from paddy fields in China, while no-till with residue removal decreased methane (CH_4) emission by 30% than that of traditional tillage practice (Zhao et al. 2016). Tillage in some cases is also found unresponsive to release N_2O from crop fields (Elmi et al. 2003).

The no-till practice may increase soil C sequestration through reducing CO_2 emission, reduce synthetic nitrogen fertilizer application, irrigation water, and fossil fuel for crop production. Therefore, the cost of crop production under no-till reduces, and so farmers will be economically benefitted. The no-till practice saves time, improves soil health, which leads to additional economic and environmental benefits. Continuous adoption of no-till farming for several years makes the soil capable to hold more water than conventionally ploughed croplands mostly in drought-prone areas. No-till implementation decreases soil loss because of wind and rain actions. Once more, it improves soil aggregation and increases C sequestration thus lessen the effects of warming of our planet (Grandy et al. 2006).

The main constraints to adopting no-till practice are unavailability of know-how including equipment and machines, traditional mindset of farmers, inadequate government policy, and unavailability of suitable weedicides for weed management (Gattinger et al. 2011; Jat et al. 2014; Farooq and Siddique 2014). *The weed management* under the no-till system is a concern and challenge. A longer time is needed to get the stabilized action of no-till on crop harvest and health improvement of the submerged soil, which is another drawback for the adoption of this technology. However, all these barriers can be removed locally mainly creating awareness among stakeholders and changing government policy. It is positive that many international and national organizations including Food and Agriculture Organization (FAO), International Fund for Agricultural Development, World Bank, European Union, French Agricultural Research Centre for International Development, Consultative Group on International Agricultural Research, Government and Non-Government Organizations are working and advocating in favour of no-till CA.

9.6.2 Minimum/Reduced Tillage

It is a resource conservation strategy in agriculture, where at least 30% of the field surface is covered by crop residues after planting. Reduced tillage (RT) contributes to reducing erosion of soil by water and wind (Laryea et al. 1991). In this crop cultivation practice, the soil is conserved allowing minimum disturbance and keeping residues spread on the ground instead of removing or incorporating into the soil. Reduced tillage is synonymous with minimum-till, strip-till, zone-till, ridge-till, no-till or permanent-bed systems (Campbell-Nelson 2019). Reduced tillage can be implemented on farms swapping from moldboard ploughs, disk-harrows, and rototillers to using less impactful tools like chisel ploughs, s-tine cultivators, and spaders. Practicing RT several years may progress towards zero tillage. Reduced tillage is a suitable tool in the conventional farming system that prevents soil degradation, improves soil structures, increases ecosystem services, and decreases production costs (Derpsch et al. 2010). It has a huge prospect to increase and sustain crop yields, improve soil fertility and increase C stock in soils (Zikeli et al. 2013). Researchers also reported reduced yields of several crops under RT compared to TT (Tables 9.5 and 9.7). Reduced tillage improves biodiversity and ecosystems and thus it has immense environmental benefits. It improves soil bio-physicochemical characteristics, restores soil health, and resolves the problems associated with excess tillage and finally mitigates negative effects of climate change.

Reduced tillage was found effective in preventing faster mineralization of SOM, which contributed to more C accumulation in soil and lower the rates of CO_2 and other GHGs emissions (Hafeez-ur-Rehman et al. 2015; Rahman et al. 2017). A study

Table 9.7 Results of reduced (RT) and traditional tillage (TT) practices on CO_2 emission, soil properties and rice yield

Treatment	Tillage practices on CO_2 emission, soil bulk density and rice yield			
	CO_2 emission (kg ha^{-1} day^{-1})	C accumulation (kg ha^{-1})	Bulk density (g cc^{-1})	Grain yield (t ha^{-1})
RT	33.92b	3813a	1.35a	5.83
TT	64.77a	1980b	1.31b	6.05
S.E. (±)	0.95	320	0.014	0.19

(Adapted, Rahman et al. 2017)

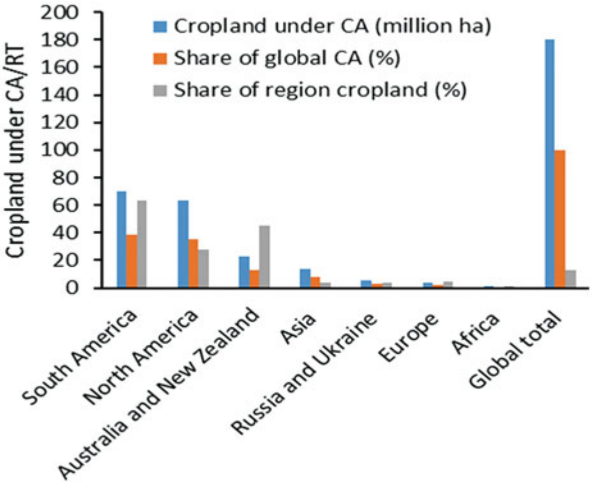

Fig. 9.7 Estimated use of conservation agriculture (CA) and by implication reduced tillage across the region during 2015–16 (Modified, Kassam et al. 2019)

of RT (2 times ploughing) and traditional tillage (TT) (4 times ploughing by a country plough), which was conducted in Bangladesh by Rahman et al. (2017) in four consecutive rice seasons revealed that RT contributed to less CO_2 emission, higher C accumulation, higher soil bulk density, and less rice yield compared to TT (Table 9.7). Reduced tillage is important from the perspective of environmentally safe gourd because crop residues help to prevent soil erosion caused by water and air and thus conserves fertile agricultural soils. Reduced tillage reduces field preparation time by 66% and reduces energy use when compared with conventional tillage (Jarvis and Woolford 2017). Thus, it provides benefits through energy-saving and soil conservation, which may attract farmers' interest in implementing RT.

The RT is getting popularity around the globe because of higher factor productivity of production inputs, increased outputs, lower production costs, better profitability, greater resilience to stresses, minimum land degradation, soil health improvement, climate change adaptation and mitigation. It is reported that over 180 million ha of croplands are under CA and RT across the globe (Fig. 9.7). It is evinced from Fig. 9.7 that America and Australia are the pioneers in adopting CA and RT, while shares of Asia, Africa, and Europe are minimal. In the Indo-Gangetic

Plains, the area under CA is about five million ha, which is insignificant about world coverage (Hafeez-ur-Rehman et al. 2015).

The main barrier of adoption of RT in crop cultivation is the mindset of farmers, where they believe that more tillage, i.e. *traditional tillage provides more crop yields. Moreover, RT increases the abundance of diseases, pest and weed infestations in crops* (Carr et al. 2012; Lehnhoff et al. 2017). Hofmeijer et al. (2019) *reported that RT increases weed infestation by 15–18%. Suitable seeding and planting equipment are lacking in the South Asian countries, which also acts as barriers of RT adoption. Farmers' motivation through training, education, social campaign,* etc. *are suggested to change their mindset in adopting RT. Establishment of industries for manufacturing of seeding and planting equipment and better solution of pest control measures may help in the adoption of RT.* The greater weed pressure especially perennial weeds under RT demands effective know-how to get rid of weeds. Selective biodegradable herbicides and organisms are recommended for a wider practice of RT in crop production. Technical and financial supports from governments, donor agencies, and international organizations are needed especially in Asia and Africa for the adoption of RT.

9.6.3 Strip Tillage

Strip tillage is one of the types of soil conservation approaches combined with zero-tillage and full-width tillage. It maintains lesser till than the full-width tillage and performs parallel to the row direction. One-fourth of the plough layer is generally being disturbed by this tillage practice. In strip-tillage soil is loosened in the tilled strips leaving the remaining area undisturbed. In this technique, narrow space cultivated and seeds are sown and fertilization is done simultaneously. In strip-tillage technique, 25–30% surface area is tilled in strip maintaining strip wide range 10–30 cm and leaving the undisturbed area between the strips varies 40–100 cm based on plant type (Al-kaisi and Yin 2005; ASAE 2013). This tillage technique is suitable for row-crops such as corn, and sunflower. By lowering the equipment and number of tillage frequency, it can conserve the soil. Strip tillage may conserve a relatively higher amount of crop residue within the strip that helps to reduce soil erosion loss (Licht and Al-Kaisi 2005). This tillage technique increases OM and nutrients in the soil and effectively control soil erosion. The soil in the strip-tillage is comparatively warmer and softer as well as less compacted than that of no-till (Cruse 2002).

Strips tilling conserve the soil water by increasing the infiltration rate of dryland agricultural soil. Organic residue in the undisturbed strip spaces reduces evaporation rate and rain flash impact. Compared to conventional tillage, strip tillage activity reduces the surface runoff approximately by 81% (Bosch et al. 2005). Strip tillage has been associated with partial soil coverage by different residual mulch, and thus preserves soil moisture. With an increase of strip width soil moisture content decreases and temperature of surface soil (5 cm depth) increases by 1–1.4 °C (Celik et al. 2013). The insulating capacity of organic residue of the strip space has significant effects on soil temperature and reduces soil dryness in spring. Strip tillage shows comparatively higher thermal conductivity due to lowering soil alteration and creating less air pocket (Licht and Al-Kaisi 2005).

Cultivation practices may considerably affect the soil structure, consistency, clod, plough pan formation, aeration, bulk density, resistance, and ground coverage (Simmons 1992). Compared to no-till and MT, strip-tillage gives lower root penetration resistant (Trevini et al. 2013). Strip tillage provides more lager size clods than that of MT due to the slow pass of strip-tiller. Strip tillage results in comparatively lower bulk density at different depth of soils due to higher OM accumulation. Moreover, compared to TT, strip-tillage provides less soil compaction by lesser frequency of traffic pass probably facilitate higher porosity, higher aggregation and WHC, and lower bulk density (Licht and Al-Kaisi 2005; Jabro et al. 2009).

Soil aggregation and its stability are affected by strip tillage. Juskulska (2019) reported that five-year intensive strip-tillage showed 57.5 and 26.7% more water-stable aggregates compared to conventional plough and plough-less cultivation, respectively. Lesser excavation, limited agricultural machinery use and greater protection of plant of residue technique of strip tillage help to augment soil aggregation (Laufer et al. 2016). Jabro et al. (2009) conveyed the message that strip-tillage ensures 23–138% higher saturated hydraulic conductivity than conventional one at 0–15 cm soil depth (Table 9.5). Strip tillage produces a greater volume of macrospore with more vertical pore connectivity, resulting in lesser bulk density and soil compaction and higher porosity indicate more saturated hydraulic conductivity (Lipiec et al. 2005; Jabro et al. 2009).

According to Juskulska (2019) five-year strip-tillage empirical data also ascribed that compared to conventional plough, strip-till technology increased OC, P, K, Mg in soils by 6.2, 11.7, 4.6, and 4.9%, respectively. Strip tillage helps to accumulate more OM in the surface soil (Awale et al. 2013). Mineralization of OM is affected by different tillage practices. Strip tillage is considered as eco-friendly soil management practice as it reduces CO_2 emission from soil (Reicosky 1998). Strip tillage reduces 19–41% CO_2 emission from agricultural soil to the atmosphere compared to moldboard tillage (Al-kaisi and Yin 2005).

Biological activity of soil is also greatly affected by the strip-tillage due to higher OM accumulation (Table 9.5). Data from a 6-year study elucidates that strip-tillage significantly increases the bacteria, fungi, and nematode population by 49, 37, and 275%, respectively, in a watermelon field (Leskovar et al. 2016). Lower alteration of topsoil helps to accelerate the microbial population microbial abundance in soil under strip tillage compared to conventional and plough-less cultivation. The long-term strip-till vegetable field also in strip-tillage (Sengupta and Dick 2015). Juskulska (2019) reported an increased number of nematode and earthworm than that of conventional moldboard plough cultivation (Overstreet et al. 2010).

9.6.4 Ridge Tillage

Ridge tillage was introduced in the early 1980s and widely accepted throughout the world with several modifications. The ridge tillage technique is a transitional development of moldboard plough tillage (MP) and no-tillage. Ridge tillage is characterized by permanent row-inter-row alignment, in which ridge is built above the planted row by cultivation (Gregorich et al. 2001). Ridge is raised above the mean land surface level and the technique has included three distinct zonal cultivation systems such as ridge centres, ridge shoulders, and inter-rows. Ridge inter-rows are maintained in the same locations every year.

Numerous empirical data summarizes that compared to no-till and MP, ridge tillage provides more soil fertility, water retention, and pest management control option (Jiang and De-Ti 2009), reduces soil erosion, decreases GHGs (Patino-Zuniga et al. 2009), increases SOC and temperature (Shao et al. 2009; He et al. 2010). Conversely, ridge tillage enhances higher P loss and soil bulk density in the surface soil compared to MP (Pikul Jr et al. 2001). Shi et al. (2012) found that Ridge tillage stimulates higher accumulation of soil C in ridges than that of furrows (Table 9.5). Soil pH is also affected by the ridge tillage practice, where continuous ridge tillage increases the soil acidity (Mloza-Banda et al. 2014).

9.6.5 Traditional/Conventional Tillage

Tillage is the mechanical manipulation or alteration of soils to make it suitable for growing crops. Tillage affects all types of soil characteristics, e.g. hydrology, nutrient dynamics, soil density, porosity, aggregation, infiltration, temperature, GHGs emissions, and OM contents (Busari et al. 2015). Traditional tillage is also known as conventional or intensive tillage practice, which involves multiple operations and leaves $<15\%$ crop residue cover. It is a form of crop cultivation technique, where farmers loosen the soil by turning it over either manually with spade/hoes or repeatedly with animal-driven ploughs or mechanical power-driven different types of discs. The modern intensive agriculture is accompanied by primary and secondary tillage with heavy machinery like tractors, rotavators, power tillers, etc. (Fig. 9.8). Such tillage practice shows considerable effects in altering the soil ecology, changing the habitats and functions of soil microorganisms, and nutrient transformation and dynamics in soil-plant systems (Schimel and Schaeffer 2012).

Traditional tillage enhances microbial decomposition of OM and shows significant negative effects on C accumulation in soils compared to RT (Alam et al. 2017; Rahman et al. 2017). It breaks down soil aggregates, enhances nutrient transformation, and increases CO_2 and N_2O emission from soils, and thus contributes to global warming through increasing temperature (Rahman et al. 2017; He et al. 2019). Li et al. (2007) reported that TT alone and with residue removal caused for the destruction of soil structure, degradation of soil health, and ecological disruption. As soil becomes more disturbed by frequent and deep ploughing, TT encourages soil erosion, which has the potential to pollute the environment. In an ongoing study

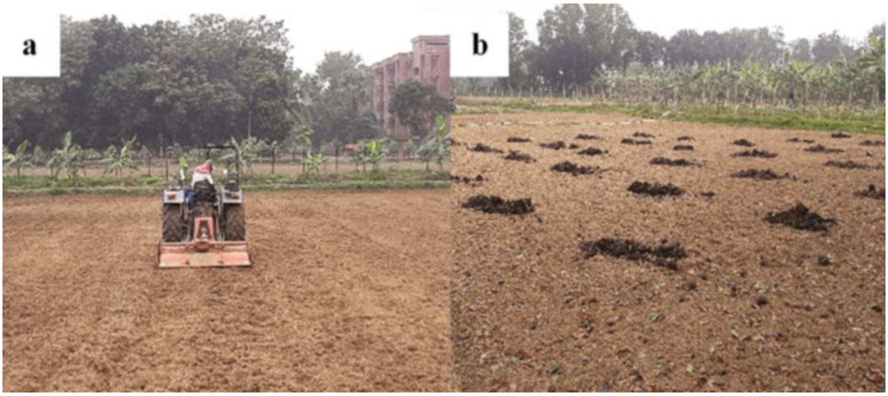

Fig. 9.8 Intensive cultivation system through traditional tillage practices in a rice field at BSMRAU research field of Bangladesh: (**a**) Secondary ploughing by rotavator, (**b**) Application of cow dung

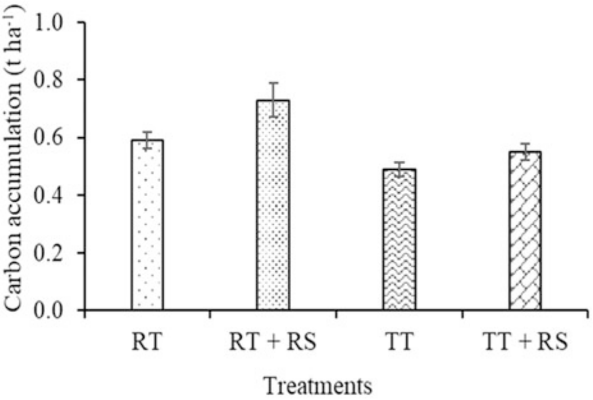

Fig. 9.9 Effects of reduced (RT) and traditional tillage (TT) on soil C accumulation with and without rice straw (RS) application in the paddy field of Bangladesh (Unpublished data)

commenced in 2017 at Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU) of Bangladesh comprising RT and TT with and without RS application found higher C accumulation in RT compared to TT in paddy field (Fig. 9.9). During the study period, a total of 6 t C ha^{-1} was applied using RS considering a C rate of 2 t ha^{-1} in a crop season. After 3 years it was found that without RS addition, RT contributed 20.42% higher C in soil, while with RS it increased 32.73% more C compared to TT. The inefficiency of TT in terms of C and other nutrient enrichment and biomass C was also attributed as presented in Tables 9.5 and 9.6. Data presented in Table 9.6 revealed that OM and biomass C in soils under TT reduced by 43, and 33%, respectively, compared to no-till.

Soil acts as a habitat of soil microorganisms and also many other animals more specifically earthworms. Tillage practices homogenize soils and exert impacts on soil biota. Through mechanical breaking down and mixing of soil, tillage practice disturbs the unique habitat of soil organisms. Many species of microorganisms are reported to be disappeared because of mechanical turmoil of soil by TT and few species becomes dominant (Sengupta and Dick 2015). It is reported that TT can also decrease earthworm populations by 2–9 times as well as their diversity in soils (Chan 2001). Soil organisms are known as soil engine, which drives the soil functions, i.e. ecosystem services.

9.7 Conclusions

It is a never-ending challenge to sustain soil health maintaining fertility and productive capacity, especially in intensive agriculture. Rational use of organic amendments and tillage practices might recover degraded and exhausted soils through increasing soil aggregates, acting as a sink of C and nutrients and harbouring soil microbes. Crop production for the days ahead needs to be increased many folds like double, triple, quadruple, and so on using the land area today we have subject to a substantial reduction in future. There are no alternatives but to improve and maintain soil health through the collective use of organic and inorganic fertilizers, adopting a need-based tillage system and other soil and crop management practices until the existence of the world.

9.8 Future Perspectives

Vienna Soil Deceleration ‘Soil matters for humans and ecosystems’ emphasized on sustainable soil management. The sensible use of organic amendments and conservation tillage practices must ensure a healthy soil and has huge potential towards achieving UN Sustainable Development Goals (SDGs). Retention of crop residues in the fields needs to be practiced to promote long-term soil health. Replenishment of OM and nutrients to crop fields using available resources increase C sequestration in soil. Combined application of fertilizers using organic and inorganic sources ensures a continuous and steady supply of nutrients to plants and reduce environmental pollution. No-till along with cover crops and crop rotation is found to be the most effective in conserving soil C and the environment. Conservation tillage like no-till, reduced tillage, and strip-tillage, etc. cause minimum damage to the environment, therefore, are recommended for farmers’ practice across the world wherever possible. Soil and crop management practices that are conducive for C sequestration might contribute to reduce CO_2 emission from soil to the atmosphere. Wider adoption of such technologies will certainly secure soil health, mitigate global warming, and climate change.

References

Abbott LK, Murphy DV (2007) Biological soil fertility: a key to sustainable land use in agriculture. Springer, London, p 254

Adebola AE, Ewulo BS, Arije DN (2017) Effects of different animal manures on soil physical and microbial properties. Appl Trop Agric 22(1):128–133

Adebusoye SA, Ilori MO, Amund OO, Teniola OD, Olatope SO (2007) Microbial degradation of petroleum hydrocarbons in a polluted tropical stream. World J Microbiol Biotechnol 23 (8):1149–1159

Adekiya AO, Ojeniyi SO, Owonifari OE (2016) Effect of cow dung on soil physical properties, growth and yield of maize (*Zea mays*) in a tropical Alfisol. Sci Agric 15(2):374–379

Adeyemo AJ, Akingbola OO, Ojeniyi SO (2019) Effects of poultry manure on soil infiltration, organic matter contents and maize performance on two contrasting degraded alfisols in southwestern Nigeria. Int J Recycl Org Waste Agric 1:1–8

Agbede TM, Ojeniyi SO, Adeyemo AJ (2008) Effect of poultry manure on soil physical and chemical properties, growth and grain yield of sorghum in southwest, Nigeria. Am Eurasian J Sustain Agric 2(1):72–77

Agegnehu G, Vanbeek C, Bird MI (2014) Influence of integrated soil fertility management in wheat and tef productivity and soil chemical properties in the highland tropical environment. J Soil Sci Plant Nutr 14(3):532–545

Akbarnia A, Alimardani R, Baharloeyan S (2010) Performance comparison of three tillage systems in wheat farms. Australian J Crop Sci 4(8):586–589

Aktar MW, Sengupta D, Chowdhury A (2009) Impact of pesticides use in agriculture: their benefits and hazards. Interdisc Toxicol 2:1–12

Akter N, Ara KA, Akand MH, Alam MK (2017) Vermicompost and trichocompost in combination with inorganic fertilizers increased growth, flowering and yield of gladiolus cultivar (GL-031) (*Gladiolus grandiflorus* L.). Adv Res 12(3):1–11

Alam MK, Salahin N, Islam S, Begum RA, Hasanuzzaman M, Islam MS, Rahman MM (2017) Patterns of change in soil organic matter, physical properties and crop productivity under tillage practices and cropping systems in Bangladesh. J Agric Sci 155(2):216–238. https://doi.org/10.1017/S0021859616000265

Alam MA, Rahman MM, Biswas JC, Akhter S, Maniruzzaman M, Choudhury AK, Jahan ABMS, Miah MMU, Sen R, Kamal MZU, Mannan MA, Shiragi MHK, Kabir W, Kalra N (2019) Nitrogen transformation and carbon sequestration in wetland paddy field of Bangladesh. Paddy Water Environ 17:677–688. https://doi.org/10.1007/s10333-019-00693-7

Al-Kaisi MM, Yin X (2005) Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soyabean rotations. J Environ Qual 34(2):437–445

Antonious GF (2016) Soil amendments for agricultural production. In: Larramendy ML, Soloneski S (eds) Organic fertilizers: from basic concepts to applied outcomes. Intech, Rijeka, pp 157–187

ASAE (2013) Terminology and definitions for soil tillage and soil-tool relationships. ASAE EP191.3, February 2005 (R2013). American Society of Agricultural Engineers, St Joseph, MI

Avnimelech Y, Cohen A, Shkedi D (1990) The effect of municipal solid waste compost on the fertility of clay souls. Soil Technol 3(3):275–284

Awale R, Chatterjee A, Franzen D (2013) Tillage and N-fertilizer influences on selected organic carbon fractions in a North Dakota silty clay soil. Soil Till Res 134:213–222

Bandyopadhyay KK, Misra AK, Ghosh PK, Hati KM (2010) Effect of integrated use of farmyard manure and chemical fertilizers on soil physical properties and productivity of soybean. Soil Till Res 110(1):115–125

Bauer A, Black AL (1992) Organic carbon effects on available water capacity of three soil textural groups. Soil Sci Soc Am J 56(1):248–254

Beare MH, Hendrix PF, Coleman DC (1994) Water-stable aggregates and organic matter fractions in conventional-and no-tillage soils. Soil Sci Soc Am J 58(3):777–786

Binte BI (2020) Effect of long term rice straw application on soil health. MS thesis, Winter 2019 term. Department of Soil Science, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, Bangladesh

Bolan NS, Hedley MJ (2003) Role of carbon, nitrogen, and sulphur cycles in soil acidification. In: Rengel Z (ed) Handbook of soil acidity. Marcel Dekker, New York, pp 29–56

Bosch DD, Potter TL, Truman CC, Bednarz CW, Strickland TC (2005) Surface runoff and lateral surface flow as response to conventional tillage and soil-water conditions. Trans ASAE 48 (6):2137–2144

Brady NC, Weil RR (1999) The nature and properties of soils. Prentice Hall, Upper Saddle River

Brady NC, Weil RR (2014) The nature and properties of soils, 14th edn. Pearson Education, Upper Saddle River

Brown S, Cotton M (2011) Changes in soil properties and carbon content following compost application: results of on-farm sampling. Compost Sci Util 19(2):87–96

Busari MA, Kukal SS, Kaur A, Bhatt R, Dulazi AA (2015) Conservation tillage impacts on soil, crop and the environment. Int Soil Water Conserv Res 3(2):119–129

Butler TJ, Han KJ, Muir JP, Weindorf DC, Lastly L (2008) Dairy manure compost effects on corn silage production and soil properties. Agron J 100(6):1541–1545

Campbell-Nelson K (2019) New England vegetable management guide. https://ag.umass.edu/vegetable/news/2018-2019-new-england-vegetable-management-guide-available-now

Carr PM, Mader P, Creamer NG, Beeby JS (2012) Overview and comparison of conservation tillage practices and organic farming in Europe and North America. Renew Agric Food Syst 27:2–6

Celik I, Ortas I, Kilic S (2004) Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. Soil Till Res 78(1):59–67

Celik A, Altikat S, Way T (2013) Strip tillage width effects on sunflower seed emergence and yield. Soil Till Res 131:20–27

Chan KY (2001) An overview of some tillage impacts on earthworm population abundance and diversity—implications for functioning in soils. Soil Till Res 57(4):179–191

Chang EH, Wang CH, Chen CL, Chung RS (2014) Effects of long-term treatments of different organic fertilizers complemented with chemical N fertilizer on the chemical and biological properties of soils. Soil Sci Plant Nutr 60(4):499–511

Channabasavanna AS (2003) Efficient utilization of poultry manure with inorganic fertilizers in wet land rice. J Maharashtra Agric Univ 27(3):237–238

Connolly RD (1998) Modelling effects of soil structure on the water balance of soil-crop systems: a review. Soil Till Res 48:1–19

Cruse RM (2002) Strip tillage effects on crop production, crop year 2001. Department of Agronomy, Lowa State Univ, Ames, IA

Das BB, Dkhar MS (2011) Rhizosphere microbial populations and physico chemical properties as affected by organic and inorganic farming practices. Am-Euras J Agric Environ Sci 10:140–150

Derpsch R, Friedrich T, Kassam A, Hongwen L (2010) Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric Biol Eng 3:1–25

Diacono M, Mantemurro F (2010) Long-term effects of organic amendments on soil fertility. A review. Agron Sustain Dev 30:401–422

Diacono M, Castrignanò A, Troccoli A, Benedetto DD, Basso B, Rubino P (2012) Spatial and temporal variability of wheat grain yield and quality in a Mediterranean environment: a multivariate geostatistical approach. Field Crop Res 131:49–62

Dimassi B, Mary B, Wylleman R, Labreuche J, Couture D, Piraux F, Cohan JP (2014) Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agric Ecosyst Environ 188:134–146

Dobermann A, Fairhurst TH (2002) Rice straw management. Better Crop Int Spec Suppl 16:7–11

Drakopoulos D, Scholberg JM, Lantinga EA, Tittonell PA (2016) Influence of reduced tillage and fertilization regime on crop performance and nitrogen utilization of organic potato. Org Agric 6 (2):75–87

Duong TT, Penfold C, Marschner P (2012) Amending soils of different texture with six compost types: impact on soil nutrient availability, plant growth and nutrient uptake. Plant Soil 354 (1–2):197–209

Elmi AA, Madramootoo C, Hamel C, Liu A (2003) Denitrification and nitrous oxide to nitrous oxide plus dinitrogen ratios in the soil profile under three tillage systems. Biol Fertil Soils 38:340–348

Ewulo BS, Hassan KO, Ojeniyi SO (2007) Comparative effect of cow dung manure on soil and leaf nutrient and yield of pepper. Int J Agric Res 2(12):1043–1048

Ewulo BS, Ojeniyi SO, Akanni DA (2008) Effect of poultry manure on selected soil physical and chemical properties, growth, yield and nutrient status of tomato. Afr J Agric Res 3(9):612–616

Fan M, Shen J, Yuan L, Jiang R, Chen X, Davies WJ, Zhang F (2011) Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. J Exp Bot 63(1):13–24

FAO (2005) The importance of soil organic matter: key to drought-resistant soil and sustained food production. FAO soils bulletin 80. FAO, Rome

FAO (2009) Global agriculture towards 2050. High level expert forum – how to feed to world in 2050. http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf

FAO (2015) Healthy soils are the basis for healthy food production. Food and Agriculture Organization of the United Nations. www.fao.org/soils-2015/news/news-detail/en/c/277682

Farooq M, Siddique KHM (eds) (2014) Conservation agriculture. Springer International, Cham. https://www.springer.com/gp/book/9783319116198

Farrell M, Jones DL (2009) Critical evaluation of municipal solid waste composting and potential compost markets. Bioresour Technol 100(19):4301–4310

Franzluebbers AJ (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Till Res 66(2):197–205

FRG (2018) Fertilizer recommendation guide. Bangladesh Agricultural Research Council (BARC) Farmgate, Dhaka, p 223

Friedrich T, Kassam A (2012) No-till farming and the environment: do no-till systems require more chemicals? Outlooks Pest Manag 23(4):153–157. https://doi.org/10.1564/23aug02

Gannett M, Pritts MP, Lehmann J (2019) Soil amendments affect soil health indicators and crop yield in perennial strawberry. Hort Tech 29(2):179–188

Gao M, Liang F, Yu A, Li B, Yang L (2010) Evaluation of stability and maturity during forced-aeration composting of chicken manure and sawdust at different C/N ratios. Chemosphere 78 (5):614–619

Garg S, Bahla GS (2008) Phosphorus availability to maize as influenced by organic manures and fertilizer P associated phosphatase activity in soils. Bioresour Technol 99(13):5773–5777

Gattinger A, Jawtusch J, Muller A, Mader P (2011) No-till agriculture – a climate smart solution? Bischofliches Hilfswerk MISEREOR e.V. Mozartstrabe, Aachen

Ge S, Zhu Z, Jiang Y (2018) Long-term impact of fertilization on soil pH and fertility in an apple production system. J Soil Sci Plant Nutr 18(1):282–293

Ghosh PK, Ramesh P, Bandyopadhyay KK, Tripathi AK, Hati KM, Misra AK, Acharya CL (2004) Comparative effectiveness of cattle manure, phosphocompost and fertilizer-NPK on three cropping systems in vertisols of semi-arid tropics. I. Crop yields and system performance. J Bioresour Technol 95:77–83

Govaerts B, Mezzalama M, Unno Y, Sayre KD, Luna-Guido M, Vanherck K, Dendooven L, Deckers J (2007) Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. Appl Soil Ecol 37(1–2):18–30

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J, Dendooven L (2009) Conservation agriculture and soil carbon sequestration: between myth and famer reality. Crit Rev Plant Sci 28:97–122

Goyal S, Singh D, Suneja S, Kapoor KK (2009) Effect of rice straw compost on soil microbiological properties and yield of rice. Indian J Agric Res 43(4):263–268

Grandy AS, Loecke TD, Parr S, Robertson GP (2006) Long-term trends in nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. J Environ Qual 35 (4):1487–1495. https://doi.org/10.2134/jeq2005.0166

Greenland DJ (1977) Soil damage by intensive arable cultivation: temporary or permanent? Philos T R Soc B 281(980):193–208

Gregorich EG, Turchenek LW, Carter MR, Angers DA (eds) (2001) Soil and environmental science dictionary. Can Soc Soil Sci 8:372

Gui-mei Z, Xiang-yong L, Min WU (2015) Effect of straw incorporation on soil fertility and yield of rice after tobacco. Fujian Agricultural Science and Technology, Fujian

Gupta R, Sayre KD (2007) Conservation agriculture in South Asia. J Agric Sci 145(3):207–214

Gupta KK, Aneja KR, Rana D (2016) Current status of cow dung as a bioresource for sustainable development. Bioresour Bioprocess 3(1):1–11

Hafeez-ur-Rehman AN, Wakeel A, Saharawat YS, Farooq M, Siddique KH (eds) (2015) Conservation agriculture in South Asia. Conservation agriculture. Springer, Cham

Hati KM, Mandal KG, Misra AK, Ghosh PK, Bandyopadhyay KK (2006) Effect of inorganic fertilizer and farmyard manure on soil physical properties, root distribution, and water-use efficiency of soybean in Vertisols of central India. Bioresour Technol 97(16):2182–2188

Havlin JL, Beaton JD, Tisdale SL, Nelson WL (2005) Soil fertility and fertilizers: an introduction to nutrient management (no. 631.422/H388). Pearson Prentice Hall, Upper Saddle River

He J, Kuhn NJ, Zhang XM, Zhang XR, Li HW (2009) Effects of 10 years of conservation tillage on soil properties and productivity in the farming–pastoral ecotone of Inner Mongolia, China. Soil Use Manag 25(2):201–209

He J, Li H, Kuhn NJ, Wang Q, Zhang X (2010) Effect of ridge tillage, no-tillage, and conventional tillage on soil temperature, water use, and crop performance in cold and semi-arid areas in Northeast China. Soil Res 48(8):737–744

He L, Zhang A, Wang X, Li J, Hussain Q (2019) Effects of different tillage practices on the carbon footprint of wheat and maize production in the loess plateau of China. J Clean Prod 23:297–305

Heggelund LR, Diez-Ortiz M, Lofts S, Lahive E, Jurkschat K, Wojnarowicz J, Svendsen C (2014) Soil pH effects on the comparative toxicity of dissolved zinc, non-nano and nano ZnO to the earthworm *Eisenia fetida*. Nanotoxicology 8(5):559–572

Heggenstaller A (2012) Managing soil pH for crop production. Crop Insights 22:1–4

Hepperly P, Lotter D, Ulsh CZ, Seidel R, Reider C (2009) Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content. Compost Sci Util 17(2):117–126

Hiel MP, Chelin M, Parvin N, Barbieux S, Degrune F, Lemtiri A, Colinet G, Degre A, Bodson B, Garre S (2016) Crop residue management in arable cropping systems under temperate climate, part 2: soil physical properties and crop production. Biotechnol Agron Soc Environ 20:245–256

Hillel D, Hatfield JL (eds) (2005) Encyclopedia of soils in the environment, vol 3. Elsevier, Amsterdam

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agric Sci 145:127–137

Hofmeijer MA, Krauss M, Berner A, Peigne J, Mäder P, Armengot L (2019) Effects of reduced tillage on weed pressure, nitrogen availability and winter wheat yields under organic management. Agronomy 9(4):180

Hole DG, Perkins AJ, Wilson JD, Alexander IH, Grice PV, Evans AD (2005) Does organic farming benefit biodiversity? Biol Conserv 122:113–130

Hoover NL, Law JY, Long LAM, Kanwar RS, Soupir ML (2019) Long-term impact of poultry manure on crop yield, soil and water quality, and crop revenue. J Environ Manag 252:109582

Hubbard RK, Bosch DD, Marshall LK, Strickland TC, Rowland D, Griffin TS, Wienhold BJ (2008) Nitrogen mineralization from broiler litter applied to southeastern coastal plain soils. J Soil Water Conserv 63(4):182–192

Hunke P, Mueller EN, Schroder B, Zeilhofer P (2015) The Brazilian Cerrado: assessment of water and soil degradation in catchments under intensive agricultural use. Ecohydrology 8 (6):1154–1180

Hussain N, Hassan G, Arshadullah M, Mujeeb F (2001) Evaluation of amendments for the improvement of physical properties of sodic soil. Int J Agric Biol 3:319–322

Jabro JD, Stevens WB, Evans RG, Iversen WM (2009) Tillage effects on physical properties in two soils of the northern great plains. Am Soc Agric Biol Eng 25(3):377–382

Jabro JD, Stevens WB, Iversen WM, Evans RG (2011) Bulk density, water content, and hydraulic properties of a sandy loam soil following conventional or strip tillage. Appl Eng Agric 27 (5):765–768

Jangid K, Williams MA, Franzluebbers AJ, Sanderlin JS, Reeves JH, Jenkins MB, Endale DM, Coleman DC, Whitman WB (2008) Relative impacts of land-use, management intensity and fertilization upon soil microbial community structure in agricultural systems. Soil Biol Biochem 40:2843–2853

Jangir CK, Singh D, Kumar S (2016) Yield and economic response of biofertilizer and fertility levels on black gram (*Vigna mungo* L.). Prog Res 11(Special-VIII):5252–5254

Jangir CK, Kumar S, Meena RS (2019) Significance of soil organic matter to soil quality and evaluation of sustainability. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 357–381

Jarvis PE, Woolford AR (2017) Economic and ecological benefits of reduced tillage. Frank Parkinson Agricultural Trust and Game & Wildlife Conservation Trust. https://www.agricology.co.uk/sites/default/files/Economic%20and%20ecological%20benefits%20of%20reduced%20tillage%20in%20the%20Uk%20-%20Final.pdf

Jat RA, Sahrawat KL, Kassam AH (eds) (2014) Conservation agriculture: global prospects and challenges. CABI, Wallingford, 393 pp

Jia S, Zhang X, Chen X, McLaughlin NB, Zhang S, Wei S, Sun B, Liang A (2016) Long-term conservation tillage influences the soil microbial community and its contribution to soil CO_2 emissions in a Mollisol in Northeast China. J Soils Sediments 16(1):1–12

Jiang XJ, De-Ti XIE (2009) Combining ridge with no-tillage in lowland rice-based cropping system: Long-term effect on soil and rice yield. Pedosphere 19(4):515–522

Juskulska I (2019) Change in soil properties after 5 years of using strip-till technology. Int Scient J Mech Agric Conserv Resour 6:193–195

Kaiser J (2004) Wounding earth's fragile skin. Science 304:1616–1618

Kakraliya SK, Kumar S, Kakraliya SS, Choudhary KK, Singh LK (2018) Remedial options for the sustainability of rice-wheat cropping system. J Pharmacogn Phytochem 7(2):163–171

Karlen DL, Mausbach MJ, Doran JW, Cline RG (1997) Soil quality: a concept, definition, and framework for evaluation. Soil Sci Soc Am J 61:4–10

Kassam A, Friedrich T, Derpsch R (2019) Global spread of conservation agriculture. Int J Environ Stud 76(1):29–51

Kaur K, Kapoor KK, Gupta AP (2005) Impact of organic manures with and without mineral fertilizers on soil chemical and biological properties under tropical conditions. J Plant Nutr Soil Sci 168(1):117–122

Kay BD (1998) Soil structure and organic carbon: a review. In: Lal R, Kimble JM, Follett RF, Stewart BA (eds) Soil processes and carbon cycle. CRC Press, Boca Raton

Kibblewhite MG, Ritz K, Swift MJ (2007) Soil health in agricultural systems. Philos T R Soc B Biol Sci 363(1492):685–701

Kimble JM, Rice CW, Reed D, Mooney S, Follett RF, Lal R (2007) Soil carbon management, economic, environmental and social benefits. CRC Press, Boca Raton

King LD (1990) Soil nutrient management in the United States. Sustainable agricultural systems. St Lucie Press, Boca Raton, pp 89–106

Kirkegaard JA, Conyers MK, Hunt JR, Kirkby CA, Watt M, Rebetzke GJ (2014) Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. Agric Ecosyst Environ 187:133–145. https://doi.org/10.1016/j.agee.2013.08.011

Kumar S, Karaliya SK, Chaudhary S (2017) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. J Curr Microbiol Appl Sci 6 (3):142–151

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, Singapore, pp 337–375. https://doi.org/10.1007/978-981-13-7264-3_10

Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 123:1–22

Laryea KB, Pathak P, Klaij MC (1991) Tillage systems and soils in the semi-arid tropics. Soil Till Res 20:201–218

Laufer DB, Loibl B, Koch MH-J (2016) Soil erosion and surface runoff under strip tillage for sugar beat (*Beta vulgaris* L.) in central Europe. Soil Till Res 262:1–7

Lehnhoff E, Miller Z, Miller P, Johnson S, Scott T, Hatfield P, Menalled F (2017) Organic agriculture and the quest for the holy grail in water-limited ecosystems: managing weeds and reducing tillage intensity. Agriculture 7(4):33

Leskovar D, Othman Y, Dong X (2016) Strip tillage improves soil biological activity, fruit yield and sugar content of triploid watermelon. Soil Till Res 163:266–273

Li H, Gao H, Wu H, Li W, Wang X, He J (2007) Effects of 15 years of conservation tillage on soil structure and productivity of wheat cultivation in northern China. Soil Res 45(5):344–350

Liang Y, Lin X, Yamada S, Inoue M, Inosako K (2013) Soil degradation and prevention in green house production. Springerplus 2(Suppl 1):S10

Licht MA, Al-Kaisi M (2005) Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Till Res 80(1–2):233–249

Lim TJ, Spokas KA, Feyereisen G, Novak JM (2016) Predicting the impact of biochar additions on soil hydraulic properties. Chemosphere 142:136–144

Lipiec L, Kus J, Slowinska-Jurkiewicz A, Nosalewicz A (2005) Soil porosity and water infiltration as influenced by tillage methods. Soil Till Res 89(2):210–220

Magdoff FR, Bartlett RJ, Ross DS (1987) Acidification and pH buffering of forest soils. Soil Sci Soc Am J 51(5):1384–1386

Maguire RO, Hesterberg D, Gernat A, Anderson K, Wineland M, Grimes J (2006) Liming poultry manures to decrease soluble phosphorus and suppress the bacteria population. J Environ Qual 35(3):849–857

Mandal B, Majumder B, Bandyopadhyay PK, Hazra GC, Gangopadhyay A, Samantaray RN, Mishra AK, Chaudhury J, Saha MN, Kundu S (2007) The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. Glob Chang Biol 13(2):357–369. https://doi.org/10.1111/j.1365-2486.2006.01309.x

Manzoni S, Porparato A (2009) Soil carbon and nitrogen mineralization: theory and models across scales. Soil Biol Biochem 41(7):1355–1379

MDA (2011) Conservation practices, Minnesota conservation funding guide. Minnesota Department of Agriculture, St Paul, MN. http://www.mda.state.mn.us/protecting/conservation/practices/constillage

Meena RS, Lal R (2018) Legumes and sustainable use of soils. In: Meena RS et al (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 1–31. https://doi.org/10.1007/978-981-13-0253-4_1

Meena RS, Kumar V, Yadav GS, Mitran T (2018) Response and interaction of Bradyrhizobium japonicum and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Kumar S, Yadav GS (2020a) Soil carbon sequestration in crop production. In: Meena RS (ed) Nutrient dynamics for sustainable crop production. Springer, Singapore, pp 1–39. https://doi.org/10.1007/978-981-13-8660-2_1

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020c) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Mitchell JP, Shrestha A, Mathesius K, Scow KM, Southard RJ, Haney RL, Schmidt R, Munk DS, Horwath WR (2017) Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA. Soil Till Res 165:325–335

Mloza-banda ML, Cornelis W, Mloza-banda HR, Makwiza CN, Verbist K (2014) Soil properties after change to conservation agriculture from ridge tillage in sandy clay loams of mid-altitude Central Malawi. Soil Use Manag 30:569–578

Mohamed AM, Sekar S, Muthukrishnan P (2010) Prospects and potential of poultry manure. Asian J Plant Sci 9:172–182

Mullens BA, Szijj CE, Hinkle NC (2002) Oviposition and development of *Fannia* spp. (Diptera: Muscidae) on poultry manure of low moisture levels. Environ Entomol 31(4):588–593

Murphy DV, Stockdale EA, Brookes PC, Goulding KWT (2007) Impact of microorganisms on chemical transformation in soil. In: Abbott LK, Murphy DV (eds) Soil biological fertility – a key to sustainable land use in agriculture. Springer, Dordrecht, pp 37–59

Norris CE, Congreves KA (2018) Alternative management practices improve soil health indices in intensive vegetable cropping systems: a review. Front Environ Sci 6:50

Nweke IA, Nsoanya LN (2015) Effect of cow dung and urea fertilization on soil properties, growth and yield of cucumber (*Cucumis sativus* L.). J Agric Ecol Res 3(2):81–88

Omonode RA, Smith DR, Gal A, Vyn TJ (2011) Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. Soil Sci Soc Am J 75(1):152–163

Orji FA, Ibiene AA, Dike EN (2012) Laboratory scale bioremediation of petroleum hydrocarbon–polluted mangrove swamps in the Niger Delta using cow dung. Malay J Microbiol 8(4):219–228

Osman KT (2013) Chemical properties of soil. In: Soils. Springer, Dordrecht, pp 97–111

Overstreet L, Hoyt G, Imbriani J (2010) Comparing nematode and earthworm communities under combinations of conventional and conservation vegetable production practices. Soil Till Res 110:42–50

Parikh SJ, James BR (2012) Soil: the foundation of agriculture. Nat Educ Knowl 3(10):2

Patino-Zuniga L, Ceja-Navarro JA, Govaerts B, Luna-Guido M, Sayre KD, Dendooven L (2009) The effect of different tillage and residue management practices on soil characteristics, inorganic N dynamics and emissions of N_2O, CO_2 and CH_4 in the central highlands of Mexico: a laboratory study. Plant Soil 314(1–2):231–241

Paul M (2003) Long-term effects of manure compost and mineral fertilizers on soil biological activity as related to soil structure and crop yield. In: Amlinger F, Nortcliff S, Weinfurtner K, Dreher P (eds) Applying compost – benefits and needs, proc. of a seminar 22–23 November 2001, BMLFUW. European Commission, Brussels

Paustian K, Six J, Elliott ET, Hunt HW (2000) Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48(1):147–163

Phogat VK, Tomar VS, Dahiya R (2015) Soil physical properties, chapter 6. In: Soil science: an introduction. Indian Society of Soil Science, New Delhi, pp 135–171

Pikul JL Jr, Carpenter-Boggs L, Vigil M, Schumacher TE, Lindstrom MJ, Riedell WE (2001) Crop yield and soil condition under ridge and chisel-plow tillage in the northern Corn Belt, USA. Soil Till Res 60(1–2):21–33

Ponnamperuma FN (1984) Straw as a source of nutrients for wet land rice. Org Matter Rice 117:136

Powlson DS, Whitmore AP, Goulding WT (2011) Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. Eur J Soil Sci 62:42–55

Rahman MM (2013) Nutrient use and carbon sequestration efficiencies in soils from different organic wastes in rice and tomato cultivation. Commun Soil Sci Plant Anal 44(9):1457–1471

Rahman MM (2014) Carbon and nitrogen dynamics and carbon sequestration in soils under different residue management. The Agriculturists 12(2):48–55

Rahman F, Rahman MM, Rahman GKMM, Saleque A, Hossain ATS, Miah MG (2016) Effect of organic and inorganic fertilizers and rice straw on carbon sequestration and soil fertility under rice-rice cropping pattern. Carbon Manag 7(1–2):41–53

Rahman MM, Biswas JC, Maniruzzaman M, Choudhury AK, Ahmed F (2017) Effect of tillage practices and rice straw management on soil environment and carbon dioxide emission. The Agriculturists 15(1):127–142

Rahman GKM, Rahman MM, Alam MS, Kamal MZ, Mashuk HA, Datta R, Meena RS (2020) Biochar and organic amendments for sustainable soil carbon and soil health. In: Datta R et al (eds) Carbon nitrogen cycling in soil. Springer, Singapore, pp 45–85. https://doi.org/10.1007/978-981-13-7264-3

Raich JW, Potter CS, Bhagawati D (2002) Inter-annual variability in global soil respiration, 1980–94. Glob Chang Biol 8:800–812

Ramos MC, Nacci S, Pla I (2003) Effect of raindrop impact and its relationship with aggregate stability to different disaggregate forces. Catena 53(4):365–376

Randhawa GK, Kullar JS (2011) Bioremediation of pharmaceuticals, pesticides, and petrochemicals with gomeya/cow dung. ISRN Pharmacol 2011:362459. https://doi.org/10.5402/2011/362459

Rani K, Sharma P, Kumar S, Wati L, Kumar R, Gurjar DS, Kumar D, Kumar R (2019) Legumes for sustainable soil and crop management. In: Meena RS, Kumar S, Bohra JS, Jat ML (eds) Sustainable management of soil and environment. Springer, Singapore, pp 193–215. https://doi.org/10.1007/978-981-13-8832-3_6

Rashad FM, Kesba HH, Saleh WD, Moselhy MA (2011) Impact of rice straw composts on microbial population, plant growth, nutrient uptake and root-knot nematode under greenhouse conditions. Afr J Agric Res 6(5):1188–1203

Reicosky D (1998) Strip tillage methods: impact on soil and air quality. In: ASSSI national soils conference, Brisbane-Australia. Australian Society of Soil Science, Brisbane, pp 56–60

Rochette P (2008) No-till only increases N_2O emissions in poorly-aerated soils. Soil Till Res 101 (1–2):97–100

Rosenstock TS, Lamanna C, Chesterman S, Bell P, Arslan A, Richards M, Rioux J, Akinleye AO, Champalle C, Cheng Z, Corner-Dolloff C, Dohn J, English W, Eyrich AS, Girvetz EH, Kerr A, Lizarazo M, Madalinska A, McFatridge S, Morris KS, Namoi N, Poultouchidou N, Ravina da Silva M, Rayess S, Ström H, Tully KL, Zhou W (2016) The scientific basis of climate-smart agriculture: a systematic review protocol. CCAFS working paper no 138. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen

Roy S, Rahman MM, Rahman GKMM, Miah MG, Kamal MZU (2019) Soil structural stability under different organic fertilizer management practices. Annals Bangladesh Agril 23(1):15–24

Ruensuk N, Mongkonbunjong P, Leuchikam C, Inthalaeng W (2008) Rice straw management in the area of continuous rice planting. Rice Res J 2:35–46

Schiesari L, Waichman A, Brock T, Adams C, Grillitsch B (2013) Pesticide use and biodiversity conservation in the Amazonian agricultural frontier. Philos Trans R Soc B Biol Sci 368 (1619):20120378

Schimel JP, Schaeffer SM (2012) Microbial control over carbon cycling in soil. Front Microbiol 3:1–11

Scotti R, Bonanomi G, Scelza R, Zoina A, Rao MA (2015) Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. J Soil Sci Plant Nutr 15(2):333–352

Sengupta A, Dick WA (2015) Bacterial community diversity in soil under two tillage practices as determined by pyrosequencing. Microb Ecol 70(3):853–859

Shao JA, Li YB, Wei CF, Xie DT (2009) Effects of land management practices on labile organic carbon fractions in rice cultivation. Chin Geogr Sci 19:241–248

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019) Growth, yield and quality of cluster bean (*Cyamopsis tetragonoloba*) as influenced by integrated nutrient management under alley cropping system. Indian J Agric Sci 89(11):1876–1880

Shi XH, Yang XM, Drury CF, Reynolds WD, McLaughlin NB, Zhang XP (2012) Impact of ridge tillage on soil organic carbon and selected physical properties of a clay loam in southwestern Ontario. Soil Till Res 120:1–7

Simmons FW (1992) Tillage and compaction effects on root distribution. In: Reetz HF Jr (ed) Proc. of roots of plant nutrition conference. Chamaign, Illinois, GA. Potash and Phosphate Institute, Manhattan, pp 61–68

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241(2):155–176

Smith SR, Jasim S (2009) Small-scale home composting of biodegradable household waste: overview of key results from a 3-year research programme in West London. Waste Manag Res 27(10):941–950

Somani LL, Totawat KL (1996) Soil conditioners and amendments, vol 1. Agrotech Publishing Academy, Udaipur, pp 28–160

Soremi AO, Adetunji MT, Adejuyigbe CO, Bodunde JG, Azeez JO (2017) Effects of poultry manure on some soil chemical properties and nutrient bioavailability to soybean. J Agric Ecol Res Int 11(3):1–10

Stanley UO (2010) Effectiveness of cow dung and mineral fertilizer on soil properties, nutrient uptake and yield of sweet potato (*Ipomoea batatas*) in southeastern Nigeria. Asian Agric Res 4:148–154

Tautges NE, Sullivan TS, Reardon CL, Burke IC (2016) Soil microbial diversity and activity linked to cropyield and quality in a dryland organic wheat production system. Appl Soil Ecol 108:258–268

Tejada M, Hernandez MT, Garcia C (2006) Application of two organic amendments on soil restoration: effects on the soil biological properties. J Environ Qual 35(4):1010–1017

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418(6898):671–677

Trevini M, Benincasa P, Guiducci M (2013) Strip tillage effect on seedbed tilth and maize production in Northern Italy as case-study for the Southern Europe environment. Eur J Agron 48:50–56

Trinsoutrot I, Recous S, Mary B, Nicolardot B (2000) C and N fluxes of decomposing ^{13}C and ^{15}N *Brassica napus* L. effects of residue composition and N content. Soil Biol Biochem 32 (11–12):1717–1730

Turmel MS, Speratti A, Baudron F, Verhulst N, Govaerts B (2015) Crop residue management and soil health: a systems analysis. Agric Sys 134:6–16

Umanu G, Nwachukwu SCU, Olasode OK (2013) Effects of cow dung on microbial degradation of motor oil in lagoon water. GJBB 2:542–548

Valpassos MAR, Cavalcante EGS, Cassiolato AMR, Alves MC (2001) Effects of soil management systems on soil microbial activity, bulk density and chemical properties. Pesq Agropec Bras 36 (12):1539–1545

Van den Putte A, Govers G, Diels J, Gillijns K, Demuzere M (2010) Assessing the effect of soil tillage on crop growth: a meta-regression analysis on European crop yields under conservation agriculture. Eur J Agron 33:231–241

Wander M (2004) Soil organic matter fractions and their relevance to soil function. In: Magdoff F, Weil RR (eds) Soil organic matter in sustainable agriculture. CRC Press, Boca Raton

Wang Z, Liu L, Chen Q, Wen X, Liao Y (2016) Conservation tillage increases soil bacterial diversity in the dryland of northern China. Agron Sustain Dev 36:28. https://doi.org/10.1007/s13593-016-0366-x

Watts DB, Torbert HA, Feng YC, Prior SA (2010) Soil microbial community dynamics as influenced bycomposted dairy manure, soil properties, and landscape position. Soil Sci 175:474–486

Weaver AR, Kissel DE, Chen F, West LT, Adkins W, Rickman D, Luvall JC (2004) Mapping soil pH buffering capacity of selected fields in the coastal plain. Soil Sci Soc Am J 68(2):662–668

Wen-Wei Z, Xiao-Jiang S, Li-Hong Z, Yue-Cai S (2011) Effects of rice straw backed to soil in double rice cropping production. Crop Res 3:10

Whalen JK, Benslim H, Jiao Y, Sey BK (2008) Soil organic carbon and nitrogen pools as affected by compost applications to a sandy-loam soil in Quebec. Can J Soil Sci 88(4):443–450

Whalley WR, Dumitru E, Dexter AR (1995) Biological effects of soil compaction. Soil Till Res 35:53–68

Wilhelm WW, Johnson JMF, Karlen DL, Lightle DT (2007) Corn Stover to sustain soil organic carbon further constrains biomass supply. Agron J 99:1665–1667

World Bank (2016) Agricultural land percent of land area. https://data.worldbank.org/indicator/AG.LND.AGRI.ZS

Zaller JG, Kopke U (2004) Effects of traditional and biodynamic farmyard manure amendment on yields, soil chemical, biochemical and biological properties in a long-term field experiment. Biol Fertil Soil 40(4):222–229

Zaman MM, Chowdhury T, Nahar K, Chowdhury MAH (2017a) Effect of cow dung as organic manure on the growth, leaf biomass yield of *Stevia rebaudiana* and post-harvest soil fertility. J Bangladesh Agric Univ 15(2):206–211

Zaman MM, Nahar K, Chowdhury T, Chowdhury MAH (2017b) Growth, leaf biomass yield of stevia and post-harvest soil fertility as influenced by different levels of poultry manure. J Bangladesh Agric Univ 15(2):212–218

Zhang Y, Liu Y, Zhang G, Guo X, Sun Z, Li T (2018) The effects of rice straw and biochar applications on the microbial community in a soil with a history of continuous tomato planting history. Agronomy 8(5):65

Zhao X, Liu SL, Pu C, Zhang XQ, Xue JF, Zhang R, Wang YQ, Lal R, Zhang HL, Chen F (2016) Methane and nitrous oxide emissions under no–till farming in China: a meta–analysis. Glob Chang Biol 22(4):1372–1384

Zikeli S, Gruber S (2017) Reduced tillage and no-till in organic farming systems, Germany— status quo, potentials and challenges. Agriculture 7(35):1–17. https://doi.org/10.3390/agriculture7040035

Zikeli S, Gruber S, Teufel C-F, Hartung K, Claupein W (2013) Effects of reduced tillage on crop yield, plant available nutrients and soil organic matter in a 12-year long-term trial under organic management. Sustainability 5:3876–3894. https://doi.org/10.3390/su5093876

Technical Efficiency in Agriculture

10

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Contents

Abstract

Resource limitations in the agricultural sector for achieving food production is one of the most critical challenges for planners and policymakers in many countries including Iran. Optimal use of available resources is one of the ways to overcome these limitations. This study aims to investigate the factors affecting technical efficiency of resource use in the agricultural sector. Classic Regression Robust (CLR) and Two Limit Tobit (TLT), M, MM and S regression were used to explore the effects of estimation techniques and study characteristics on Mean Technical Efficiency (MTE) level. The results are based on a total of 55 studies covering the 1994–2015 period. The econometric results indicate that year of

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publication, agronomic production, the functional form assumed for estimation (such as Stochastic Frontier production Function, Cobb–Douglas and Translog function) have a positive effect on the estimated MTE. On the other hand, livestock production, sample size and some model variables and cross-section have an adverse impact. Farms with livestock production have their MTE lowered by 0.03–0.06 units. Similarly, farms located in cold and humid climate regions had a lower MTE by 0.08–0.12 units. However, studies for the cold and mountainous regions reported higher MTE by 0.03–0.06. According to research results, we suggest that to achieve an overall result, policymakers and researchers can use Meta-regression analysis along with other models.

Keywords

Parametric method · S regression · Robust regression · Two limit Tobit

Abbreviations

ATE	Average technical efficiency
CLR	Classic regression robust
DEA	Data envelopment analysis
MMR	MM regression
MR	M regression
MTE	Mean of technical efficiency
OLS	Ordinary least squares
SFA	Stochastic frontier analysis
SR	S regression
TE	Technical efficiency
TLT	Two limit Tobit

10.1 Introduction

Agriculture is one of the most important economic sectors in developing countries, such as Iran, linking food security to agricultural production (Lobell et al. 2008; Verardi and Croux 2008). Furthermore, the agricultural sector has a significant share in creating employment, economic growth and non-oil foreign exchange earnings (Meena et al. 2016, 2017, 2018). Besides, this sector provides raw materials for other commercial areas (Dandekar 1986; Gardner 2003) and creates further value-added products. Specialists and experts always criticize farmers for using excessive inputs. They claim that the optimal use of inputs in this sector can be a sufficient approach for the promotion of agricultural production and food self-sufficiency (Mulwa et al. 2009). The evaluation of agricultural production efficiency is the main issue in the process of agricultural development in developing countries, which is a useful tool for designing a correct strategy (Khan et al. 2010). The vital role of efficiency in increasing the agricultural output has been admitted by many researchers, such as

Liu and Zhuang (2000); Aldaz and Millan (2003); Song et al. (2008); Păun et al. (2012); Mugera and Ojede (2014); Han et al. (2014); Zhang (2015); Nowak et al. (2015); Kumar et al. (2017); Meena et al. (2020)

Analysis of technical efficiency (TE) in agriculture is an essential issue in Iran because any improvements in it could bring significant increases in total factor productivity growth (Brümmer et al. 2006). Several studies have been undertaken on the subject of evaluation of TE in Iran. The researchers have used different methodologies for calculating it. The data envelopment analysis (DEA) and stochastic frontier analysis (SFA) have most frequently been used in these studies, particularly those for the agriculture industry. Data envelopment analysis (DEA) is a non-parametric method that involves the use of mathematical programming methods (Charnes et al. 1978). Stochastic frontier analysis (SFA) is a parametric technique, which uses econometric techniques (Aigner et al. 1977). However, studies have indicated that the selection of the type of methodology could affect the estimated TE levels (Bravo-Ureta et al. 2007).

This study attempts to explain the variability in the estimates of mean of technical efficiency (MTE) in the agricultural sector of Iran. Data from 63 TE studies were used to undertake a meta-analysis of TE levels. All of these studies focused on the agricultural sector of Iran over the 1994–2015 period. An attempt was made to answer the following research questions:

1. Did the average technical efficiency (ATE) of Iranian agriculture improve over the 1994–2015 period?
2. Did functional form influence on estimated MTE for a given study?
3. Did the sample size and number of inputs used to influence the level of estimated MTE?
4. Are there differences in MTE across different agricultural activities?
5. Could the climate differences among the studies influence the reported MTE?
6. Could the type of development region influence the reported MTE? and.
7. Could the level of risk regions influence the reported MTE?

The major contribution of this paper is that for the first time, this study has investigated the effect of factors, such as the type of climate and level of risk regions, on the estimated MTE. Furthermore, the method of meta-regression has been used to analyse TE in Iranian agriculture and explain the differences in the estimated MTE by other studies. Besides, no other study has used M, MM and S regression to analyse the TE in agriculture.

The organizational structure of the paper is as follows: (1) Literature review in Sect. 10.2, focusing on studies that have identified the active factors on TE by using a meta-regression analysis; (2) Discussion study methodology including data sources and descriptive statistics and specification of models in Sect. 10.3; (3) Discussion of results in Sect. 10.4 and (4) Summary and conclusions in Sect. 10.5.

10.2 Literature Review

In this section, an attempt is made to present a summary of the methodology followed and results from available studies related to TE and meta-analysis. Thiam et al. (2001) identified the factors that influence estimates of TE. They utilized a data set of 51 observations of TE from 32 research cases. The results of the two limit Tobit showed that Cobb–Douglas functional form and cross-sectional data produced a lower level of TE. On the other hand, independent variables as crop type, the number of variables in the model, sample size and stochastic versus deterministic frontiers have not significantly impacted TE across studies.

Bravo-Ureta et al. (2007) utilized a meta-regression analysis comprising 167 TE types of research from developed and developing countries. The results showed that stochastic frontier models created lower mean TE than the non-parametric deterministic models. Also, the results utilising parametric deterministic frontier models produce significantly lower TE levels than the stochastic models. Mean TE is higher for animal production than for crop farming.

Ogundari and Brümmer (2011) used a meta-regression analysis for identification of the factors driving the efficiency level in Nigerian agriculture. The results of the study showed that TE of researchers in the south-east and south are significantly lower. Also, they found that cash crops are considerably higher than non-cash crops. Furthermore, the authors demonstrated that year of publication from the studies has a positive impact and significant on TE.

Djokoto et al. (2016) utilized a meta-analysis on agribusiness in Ghana. In this study, they employed a fractional regression model for data analysis. The results showed that panel data models produce lower MTE than time series models. Also, the Cobb–Douglas and translog function estimated lower MTE than models without functional forms and distance production. Also, there are other studies in the literature which have focused on meta-regression and TE (Thiam et al. 2001; McDonald 2009; Ogundari 2013; Iliyasu et al. 2014; Ogundari 2014; Assaf and Josiassen 2016). Table 10.1 shows a summary of some relevant studies with their main feature and methodology.

10.3 Study Methodology

10.3.1 Discussion of Data Sources and Descriptive Statistics

The investigation of the literature on the estimation of TE in Iranian agriculture generated a total of 55 published studies, which were used for the meta-analysis for the present study. These studies were published between 1994 and 2015. Table 10.2 presents the details of all the papers utilized in this research, which included the first author name, year of publication, area (province), sample size, MTE (using deterministic and stochastic methods). Table 10.3 shows the analysis of TE based on the estimation method, type of data and functional form. The results show that the stochastic process has higher MTE (73%) than other methods. For the type of

Table 10.1 Summary of literature related to the estimation of technical efficiency

Methodology	Case	Country/ Territory	Reference
Ordered probit and binary probit	Agriculture	–	Minviel and Latruffe (2017)
two limit Tobit	Agriculture	Brazil	Mareth et al. (2016)
Ordinary least squares (OLS), two limit Tobit	Aquaculture	Asia, Africa, Europe and the USA	Iliyasu et al. (2014)
OLS	Hospital	Iran	Kiadaliri et al. (2013)
Fixed effects Tobit model, random effects Tobit model	Agriculture	–	Odeck and Bråthen (2012)
Iteratively re-weighted least squares method, generalized least squares random effect, OLS, two limit Tobit	Bank	USA	Iršová and Havránek (2010)
Truncated regression	Agriculture	Nigeria	Kolawole (2009)
Fixed effects, averaged model	Agriculture	Studies published in English and Spanish	Moreira López and Bravo-Ureta (2009)
OLS, two limit Tobit	Agriculture	Developing and developed countries	Bravo-Ureta et al. (2007)

data, studies using time series yielded a higher MTE (85%) than those using cross-section (71%) and panel data (76%). This result is in line with the findings of Thiam et al. (2001) and Bravo-Ureta et al. (2007). Finally, Table 10.3 suggests that studies using Translog functional form (74%) displayed a significantly higher MTE than studies using a Cobb–Douglas (72%) and Transcendental (72%) functional form, which is also consistent with that reported by Bravo-Ureta et al. (2007).

Table 10.4 summarizes ATE according to the agricultural activities. The highest MTE is for agronomic activities (76%), and lowest MTE is for livestock activities (66%). Also, the factors, such as level of production risk, type of climate and regional development, can affect TE. Therefore, the research data were classified based on the level of production risk, climate conditions and local development (Fig. 10.1). For dividing the areas based on the level of risk and regional development, results of studies by Najafi (2003) were used. The cold mountain areas in Iran yielded a higher MTE (74%) than other regions (Table 10.4). Also, this table illustrates that MTE for the regions with a low level of risk (75%) produces a significantly higher MTE. Table 10.5 also shows that the highest MTE is for the areas that have a low-risk level. Also, in this table, MTE for the regions with a low level of development (75%) is the highest than the areas with a high level of development (70%).

Table 10.2 Overview of empirical studies of technical efficiency in Iranian agriculture

First author	Year	Location	Product	Sample size	Mean of technical efficiency	
					Deterministic	Stochastic
Esfandyari	2010	Fars	Rice	144	–	83
Eshraghi	2011	Gorgan	Dairy cow	33	–	71
Ashrafi	2011	Khorasan Razavi	Pomegranate	127	–	69
Aghapour Sabaghi	2010	Dashtestan	Data	130	–	63
Aghapour	2011	Kerman	Pistachios	109	–	80
Bagheri	2008	Rey and Varamin	Wheat	106	–	87.5
Bagheri	2009	Esfahan	Sugar beet	85	–	76.7
Borimnejad	2006	Qom	Wheat	149	–	83
Borimnejad	2008	Esfahan	Calf	100	–	79.3
Pourjafari	2011	Gilan	Tea	72	–	58.69
Pourmoghadam	2012	Khorasan Razavi	Barely	300	–	76
Pish Bahar	2012	Sanandaj	Strawberry	129	–	83
Torkamani	2004	Abadeh	Wheat	145	–	70.65
Torkamani	2002	Fars	Sugar beet	50	–	55
Torkamani	2000	Fars	Broiler chicken	192	–	86
Torkamani	2002	Fars	Calf	50	–	71.45
Taghizadeh	2012	Savejbolagh	Strawberry	65	–	79
Hajian	2005	Boshehr	Shrimp	125	–	67
Hasanpour	2002	Kohgiloye Va Boyer Ahmad	Graps	82	–	63.8
Hasanpour	2000	Fars	Figs	191	–	69.81
Hosseinzadeh	1999	Tabriz	Onion		–	74
Khosravirad	2014	Khuzestan	Sugar cane	182	–	78.15
Khwaje Hasani	2012	Zanjan	Wheat		–	93.5
Daneshvar	2007	Kerman	Cucumber	75	–	77

Darijani	2011	Gorgan	Meat Chichens	30	–	57.66
Dashti	2012	Saghez Va Keliae	Meat Chichens	100	–	82.17
Dorandish	2012	Khorasan Jonobi	Barberry	90	–	81
Dorandish	2013	Khorasan Shomali	Dairy cow	160	–	93
Dehghanian	2001	Khorasan Shomali	Potato	45	–	65.6
Alavi	2013	Kerman	Cucumber	75	–	77
Ghorbani	2013	Gilan	Calf	70	47.02	
Kiani	2000	Esfahan	Bee	70	–	43
Godarzi	2005	Mazandaran	Rice	200	–	78.7
Mohades	1996	Mazandaran	Rice		–	90
Moradi	2005	Kerman	Potato		–	89.2
Mazhari	1996	Khorasan Razavi	Wheat		78	
Mansouri	2012	Fars	Meat chickens	304	–	83.3
Mosavi	2005	Shahrekord	Wheat	29	–	78
Mosavi	2007	Shahrekord	Potato	30	81.85	
Mahjor	2011	Fars	Meat cow	70	–	71
Rahnavard	2013	Markazi	Calf	102	49.2	
Rahmani	2001	Kohgiloye Va Boyer Ahmad	Wheat	211	–	63.5
Zare	2005	Khorasan Razavi	Grapes	83	–	61
Seyedan	2005	Hamedan	Sugar beet	144	–	71.5
Seyedan	2004	Hamedan	Garlic	148	–	74
Shafie	2006	Kerman	Sugar beet	150	–	81
Shamsoldin	2000	Fars	Rice	146	–	85
Shirvanian	2009	Estahban	Figs	90	–	22.48
Shirvanian	2005	Darab	Wheat	73	–	73.17
Salehi	2003	Khorasan Jonobi	Wheat	150	–	93.72
Sabouhi	2009	Khorasan Jonobi	Cotton	60	–	63

(continued)

Table 10.2 (continued)

First author	Year	Location	Product	Sample size	Mean of technical efficiency	
					Deterministic	Stochastic
Abdollahi	2010	Azerbaijan Sharghi	Greenhouse cucumber	127	57	93
Abdpour	2012	Yazd	Greenhouse cucumber	125	–	79

Table 10.3 The analysis of technical efficiency based on estimation method, type of data and functional form

Category	Frequency	Mean	Standard deviation	Max	Min
Estimation method					
Parametric	63	0.72	0.01	0.93	0.22
Stochastic	58	0.73	0.01	0.93	0.22
Deterministic	5	0.62	0.07	0.81	0.47
Type of data					
Cross-section	56	0.71	0.01	0.93	0.22
Time series	5	0.85	0.03	0.93	0.78
Panel	2	0.76	0.02	0.78	0.74
Functional form					
Cob- Douglas	44	0.72	0.02	0.93	0.22
Translog	15	0.74	0.03	0.93	0.47
Transcendental	4	0.72	0.05	0.86	0.63

Table 10.4 The analysis of technical efficiency based on the type of agricultural activities

Activities	Frequency	Mean	Standard deviation	Max	Min
Agronomic	28	0.76	0.01	0.93	0.55
Horticultural	21	0.71	0.03	0.93	0.22
Livestock	14	0.66	0.04	0.93	0.43

10.3.2 Specification of Models

To explain differences in the estimated level of MTE by various studies, several attributes were included in the meta-analysis. These included: sample size, functional form, year of publication, number of inputs, type of agricultural activities, climate regions and level of risk and development of areas. These variables were hypothesized to affect the reported level of MTE by selected studies. This study used three models to investigate the relationship between attributes of these studies and MTE, as shown in Eqs. (10.1), (10.2) and (10.3).

$$\text{Model 1} \quad \mathrm{MTE} = f(\mathrm{YP}, \mathrm{PAG.PLI}, \mathrm{FD}, \mathrm{MOF}, \mathrm{PCO}, \mathrm{PTR}, \mathrm{CLM}, \mathrm{CLC}, \mathrm{CLH}, \mathrm{NI}, \mathrm{NO}) \tag{10.1}$$

$$\text{Model 2} \quad \mathrm{MTE} = f(\mathrm{YP}, \mathrm{PAG.PLI}, \mathrm{FD}, \mathrm{MOF}, \mathrm{PCO}, \mathrm{PTR}, \mathrm{DEVL}, \mathrm{DEVM}, \mathrm{NI}, \mathrm{NO}) \tag{10.2}$$

$$\text{Model 3} \quad MTE = f(\mathrm{YP}, \mathrm{PAG}, \mathrm{PLI}, FD, \mathrm{MOF}, \mathrm{PCO}, \mathrm{PTR}, RIM, RIH, \mathrm{NI}, \mathrm{NO}) \tag{10.3}$$

where MTE is the mean technical efficiency reported by a study;

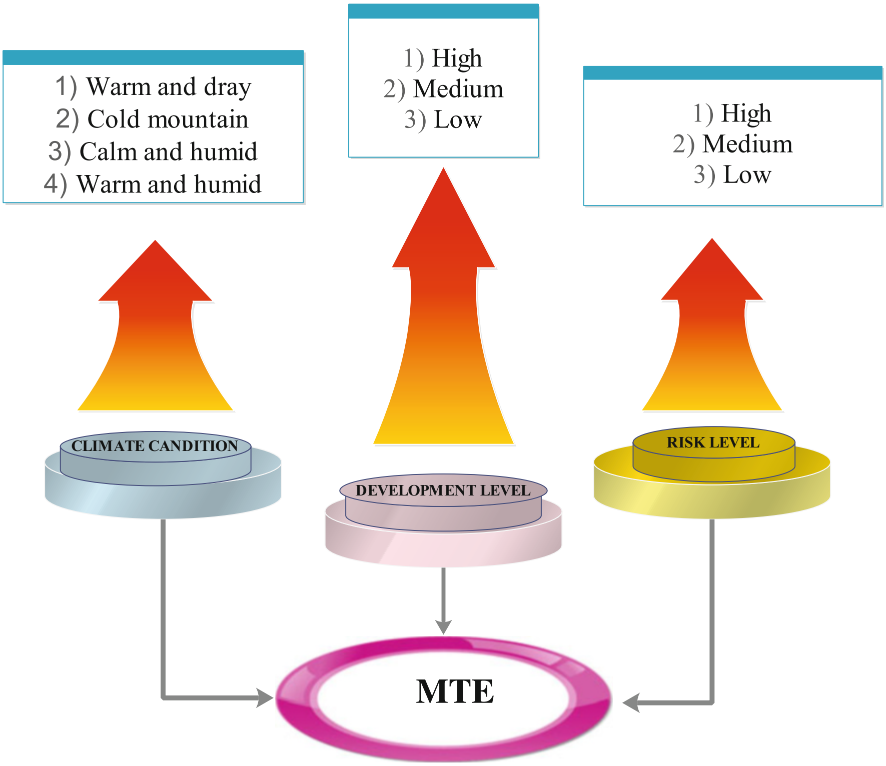

Fig. 10.1 The classification of the type of climate, development level and risk level

Table 10.5 The analysis of technical efficiency based on climate, risk and development of areas

Category	Frequency	Mean	Standard deviation	Max	Min
Climate					
Warm and dry	35	0.72	0.02	0.93	0.22
Cold mountain	16	0.74	0.03	0.93	0.51
Calm and humid	8	0.70	0.05	0.90	0.47
Warm and humid	4	0.73	0.05	0.87	0.63
Risk					
High	36	0.72	0.02	0.93	0.22
Medium	9	0.69	0.05	0.87	0.43
Low	18	0.75	0.02	0.93	0.63
Development					
High	11	0.70	0.04	0.87	0.43
Medium	43	0.72	0.02	0.93	0.22
Low	8	0.75	0.04	0.93	0.51

YP is the year of publishing;

PGA is a dummy variable that takes a value one if the model is for agronomic activities; zero otherwise.

PLI is a dummy variable that takes a value one if the model is for livestock activities; zero otherwise.

FD is a dummy variable that takes a value one if the study used cross-section data; zero otherwise.

MOF is a dummy variable that takes a value one if the study employed the stochastic frontier analysis; zero otherwise.

PCO is a dummy variable that takes a value one if the study employed Cobb–Douglas functional form; zero otherwise.

PTR is a dummy variable that takes a value one if the study used translog functional form; zero otherwise.

CLM is a dummy variable that takes a value one if the region of analysis was in the cold mountain area,

CLC is a dummy variable that takes a value one if the part of the analysis was calm and humid area; zero otherwise.

CLH is a dummy variable that takes a value one if the region of analysis was a warm and humid area; zero otherwise.

DEVL is a dummy variable that takes a value one for low development area; zero otherwise.

DEVM is a dummy variable that takes a value one for common development area; zero otherwise.

RIM is a dummy variable that takes a value one for medium risk area; zero otherwise,

RIH is a dummy variable that takes a value to one for the high-risk area; zero otherwise and.

NO and NI are the number of observations used for estimation, and the number of inputs, respectively.

In this study, we utilize Two Limit Tobit (TLT), Ordinary Least Square (OLS) and M Regression (MR), MM Regression (MMR), S Regression (SR) for the meta-regression analysis. The reasons for using these models are explained as follows:

Two Limit Tobit (TLT) Many studies used for this meta-regression for identification of factors affecting TE have employed TLT and other models (Thiam et al. 2001; Bravo-Ureta et al. 2007; McDonald 2009; Kolawole 2009; Iliyasu et al. 2014; Mareth et al. 2016; Assaf and Josiassen 2016). In this method, there is an expectation that the estimated TE score would lie between 0 and 1. Hence, in this study, censored regression models (such as the TLT) was employed as a competing model. Further information can be found in Amemiya (1973) and Tobin (1958).

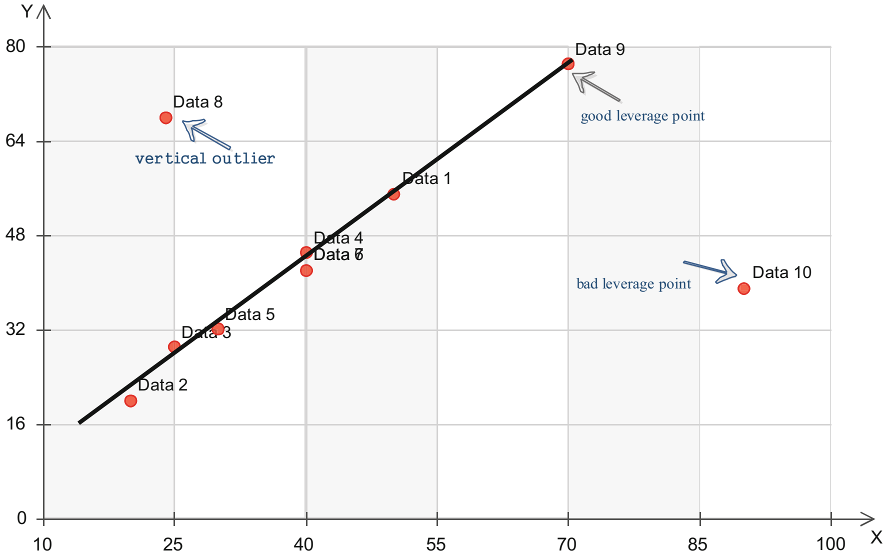

Fig. 10.2 Outliers in regression analysis

Ordinary Least Square (OLS) Investigation of literature review shows that OLS and TLT are usually used together for MTE analysis (Thiam et al. 2001; Bravo-Ureta et al. 2007; McDonald 2009; Kolawole 2009; Iliyasu et al. 2014; Mareth et al. 2016; Assaf and Josiassen 2016). However, we present OLS estimates for comparison.

M Regression (MR), MM Regression (MMR) and S Regression (SR) There are three types of outliers in the analysis of OLS: (1) Good leverage points, (2) Vertical outlier and (3) Lousy leverage points (Rousseeuw and Leroy 2005). Figure 10.2 shows the position of three points in a simple linear regression.

'Data 8' in this figure is a vertical outlier since it is outlying in the space of the dependent variable (Y-dimension), but associated with a non-outlying value in the dimension of the independent variable (X-dimension). Similarly, 'Data 10' in Fig. 10.2 is a poor leverage point since it is an outlying value in the space of independent variable and at the same time being located far from the regression line. Other data points, such as 'data 9', is an excellent leverage point. These points are located close to the regression line. Since, these outliers affect both the intercept and the slope (Verardi and Croux 2008), it is necessary to use methods that would adjust this problem.

In this study, we utilized the robust regression because of the distribution of the residuals was not normal, and outliers were present. Figure 10.3 shows the leverage against the residual squared for research data. There are some points in the above right quadrant that they can affect the results of the OLS model. Therefore, we need to use robust regression instead of OLS regression to estimate this model. In this

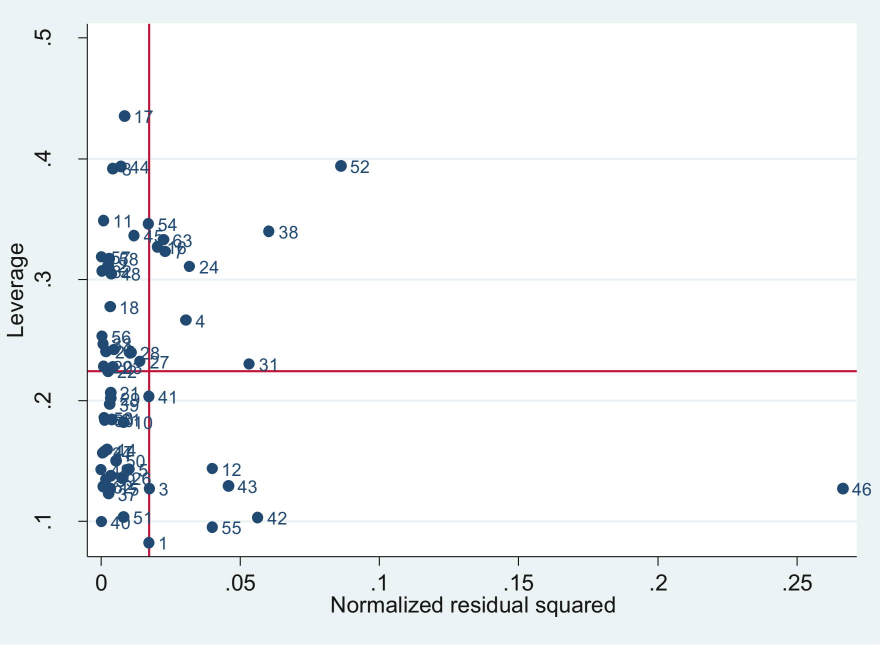

Fig. 10.3 Diagnostic plot of leverage and normalized residual squared

study, we utilized the M, S and MM regressions that are robust regression models. More details on these models are provided in Verardi and Croux (2008) and Susanti and Pratiwi (2014).

10.4 Results

All the three models represented in Eqs. (10.1), (10.2) and (10.3) were estimated using the five estimation methods—OLS, the two-limit Tobit, M, MM and S model. Results for the Model 1 are presented in Table 10.6, while those for Model 2 and Model 3 are in Tables 10.7 and 10.8, respectively. According to the results, it seems that the OLS estimates are quite similar to the two-limit Tobit model. This is perhaps because there are no observations that are censored from both sides (0 and 1). On the other hand, the robust regression (M, MM and S) estimates represented better estimates compared to the OLS and two-limit Tobit models. These results were predictable because of the non-normal distribution of residual errors and outlier data. Therefore, in this section, we will concentrate on the findings based on the M, MM and S models.

In Models 1, 2 and 3, the parameter for YP (the effect of time) is positive and significant in the S regression. This result shows that MTE has increased significantly over the study period when the impact of other variables is removed. The

Table 10.6 The result of meta-regression (Model 1)

Variable	CLR	TLT	M	MM	S
YP	−0.002 (0.010)	−0.002 (0.009)	0.0007 (0.013)	0.011 (0.018)	***0.020 (0.007)
PAG	**0.095 (0.042)	0.095 (0.037)	***0.76 (0.029)	**0.067 (0.029)	***0.111 (0.024)
PLI	**−0.027 (0.055)	-0.027 (0.048)	−0.046 (0.048)	0.065− (0.052)	0.001−- (0.021)
FD	*−0.119 (0.060)	**−0.119 (0.053)	***−0.145 (0.053)	***0.187- (0.052)	***0.197- (0.026)
MOF	**0.170 (0.064)	***0.170 (0.056)	***0.194 (0.064)	**0.200 (0.080)	***0.232 (0.028)
PCO	−0.029 (0.087)	−0.029 (0.704)	0.024 (0.063)	***−0.352 (0.107)	*0.051 (0.028)
PTR	−0.44 (0.091)	0.044 (0.586)	0.090 (0.069)	***−0.279 (0.089)	***0.148 (0.032)
CLM	0.031 (0.45)	0.031 (0.040)	0.042 (0.035)	*0.060 (0.033)	*0.034 (0.019)
CLC	−0.083 (0.049)	−0.083 (0.043)	−0.092 (0.041)	***-0.100 (0.037)	***−0.131 (0.033)
CLH	0.009 (0.056)	0.009 (0.049)	0.023 (0.052)	0.078 (0.071)	0.016 (0.003)
NI	0.003 (0.006)	0.003 (0.005)	0.001 (0.005)	−0.002 (0.005)	**−0.008 (0.005)
NO	−0.0001 (0.0002)	−0.0001 (0.0002)	*-0.0003 (0.0002)	***−0.0005 (0.0002)	****−0.0004 (0.0001)
Constant	***−15.328 (4.115)	***−15.328 (3.615)	***−15.98 (3.60)	***−14.615 (5.505)	***−10.883 (3.983)

CRC Classic regression robust, *TLT* Two limit Tobit
The number in parentheses shows the standard deviation
Source: Research finding
Significant at the 10% level; **Significant at the 5% level; ***Significant at the 1% level
The number in parentheses shows the standard deviation

positive sign and statistical significance of the parameter for PGA indicate that MTE is higher for agronomic activities than for other activities. Also, PLI reduces MTE, as seen in Models 2 and 3. This also suggests that the presence of livestock activities on a farm, on average, reduces the level of MTE, holding other variables constant.

The estimated parameter for FD (cross-sectional data) is negative and significant. This result indicates that although parametric models using cross-sectional data produce lower MTE than other data, the effect is not statistically significant. The result confirms the results obtained by Bravo-Ureta et al. (2007) and Odeck and Bråthen (2012). The parameter for MOF is positive and significant. Thus, this suggests that the stochastic frontier analysis produce higher MTE estimates than other approaches. In Model 1, the coefficient of PCO is positive and significant in S regression and is negative and significant in MM regression. But according to the

Table 10.7 The result of meta-regression (Model 2)

Variable	CLR	TLT	M	MM	S
YP	−0.004 (0.009)	−0.004 (0.008)	−0.004 (0.008)	0.0008 (0.007)	***0.012 (0.004)
PAG	*0.084 (0.055)	**0.084 (0.038)	***0.071 (0.033)	**0.063 (0.027)	***0.048 (0.018)
PLI	−0.046 (0.052)	−0.046 (0.046)	*−0.065 (0.036)	**-0.068 (0.029)	−0.032 (0.020)
FD	**−0.106 (0.04)	**−0.106 (0.045)	***−0.107 (0.053)	***−0.138 (0.036)	***−0.117 (0.024)
MOF	*0.157 (0.078)	**0.157 (0.069)	***0.175 (0.054)	***0.230 (0.044)	***0.248 (0.030)
PCO	−0.038 (0.082)	−0.038 (0.073)	−0.004 (0.054)	−0.051 (0.044)	0.038 (0.030)
PTR	0.033 (0.087)	0.033 (0.078)	−0.056 (0.060)	**−0.120 (0.049)	***0.115 (0.033)
DEVL	−0.017 (0.049)	−0.017 (0.043)	−0.019 (0.050)	*-0.031 (0.041)	*-0.054 (0.028)
DEVM	−0.035 (0.047)	−0.035 (0.042)	−0.033 (0.042)	*−0.063 (0.034)	***−0.079 (0.024)
NI	0.003 (0.005)	0.003 (0.005)	0.002 (0.006)	−0.0007 (0.005)	**0.0006 (0.003)
NO	−0.00007 (0.0001)	−0.00007 (0.0001)	*−0.033 (0.042)	−0.0002 (0.0001)	−0.00005 (0.0001)
Constant	***−15.328 (4.115)	***−13.084 (4.015)	***−13.804 (4.433)	***−13.802 (3.619)	***−7.749 (2.489)

CRC Classic regression robust, *TLT* Two limit Tobit
Source: Research finding
Significant at the 10% level; **Significant at the 5% level; ***Significant at the 1% level
The number in parentheses shows the standard deviation

results of previous studies (Ogundari et al. 2012; Iliyasu et al. 2014), the result of the S regression is acceptable. This parameter is not significant in Model 2 and Model 3. The PTR variable is positive and significant in S regression (Models 1, 2 and 3) and M regression (Model 3) and negative and significant in MM regression (Models 1, 2 and 3). But, the results of S regression conforms to other studies, notably Djokoto et al. (2016).

Model 1 introduces the additional variables where the studies are categorized according to climatic conditions. In Model 1, the coefficient for CLM is positive and statistically significant in MM and S regression. These results imply that the agricultural activities in this climate, on average, have the highest levels of MTE among all environment. The estimated parameter for CLC is negative and significant; this result shows that the agricultural activities in the regions with a calm and humid climate, on average, have the lowest estimate of MTE. The CLH is positively affected MTE but the coefficient was not statistically significant. Model 2 presents the additional variables where the observations are categorized according to the level of development of the region. The parameters for DEVL and DEVM display the

Table 10.8 The result of meta-regression (Model 3)

Variables	CLR	TLT	M	MM	S
YP	−0.001 (0.011)	−0.001 (0.010)	−0.0027 (0.008)	0.001 (0.008)	***0.023 (0.006)
PGA	0.094 (0.046)	**0.094 (0.0407)	**0.077 (0.034)	**0.076 (0.032)	**0.085 (0.023)
PLI	−0.033 (0.050)	−0.033 (0.044)	*−0.058 (0.037)	**−0.082 (0.034)	−0.078 (0.025)
FD	*−0.114 (0.057)	**−0.144 (0.050)	***−0.118 (0.042)	***−0.116 (0.039)	***−0.270 (0.029)
MOF	**0.158 (0.071)	**0.158 (0.062)	**0.191 (0.052)	***0.206 (0.049)	***0.242 (0.036)
PCO	−0.051 (0.080)	−0.032 (0.063)	−0.013 (0.053)	−0.068 (0.050)	0.075 (0.036)
PTR	0.051 (0.080)	0.051 (0.070)	***0.083 (0.059)	**−0.142 (0.055)	***0.204 (0.040)
RIM	−0.014 (0.046)	−0.041 (0.041)	−0.024 (0.050)	0.031 (0.032)	*0.0703 (0.024)
RIH	−0.041 (0.047)	−0.014 (0.040)	−0.009 (0.042)	−0.007 (0.032)	***−0.0048 (0.023)
NI	0.002 (0.009)	0.002 (0.008)	0.002 (0.006)	−0.0003 (0.005)	0.0009 (0.004)
NO	−0.0001 (0.0002)	−0.0001 (0.0002)	−0.0002 (0.042)	*−0.0003 (0.0001)	−0.0009 (0.0001)
Constant	***−12.191 (6.052)	**−12.191 (5.330)	***−14.006 (4.479)	***−12.802 (3.619)	***−7.158 (3.091)

CRC Classic regression robust, *TLT* Two limit Tobit

negative and significant effect on MTE in MM and S regression. This finding indicates that the agricultural activities in the regions with a low level of development and a medium level of development, on average, have less estimate of MTE than those areas with the high level of development.

In Model 3, the variables RIM and RIH capture the effect of the risk levels of regions on MTE estimates. The results of Table 10.8 indicate that the coefficient for RIM is positive and significant (S regression), which implies that the agricultural activities in the regions with a medium level of risk, on average, have the highest estimate of MTE than other areas. Also, RIH has a negative and statistically significant effect, implying that the agricultural activities in the regions with a high level of risk, on average, have a lower estimate of MTE than other areas.

The parameter for NI is positive and significant in Model 2, and negative and significant in Model 1. But according to previous studies such as Thiam et al. (2001), the results of Model 2 can be acceptable. The econometric results indicate that NO has a negative and significant effect in the M, MM and S regression for Model 1, M regression for Model 2 and MM regression for Model 3.

10.5 Summary and Conclusions

This study provides an overview of MTE in the agricultural sector of Iran. This study aimed to use a meta-regression analysis to clarify the variation in MTE. For this reason, a total of 55 published papers were included in the analysis. To explain the variability on these reported estimates, we regressed the MTE on the explanatory variables which included sample size, number of inputs, year of publishing, the type of agricultural activities, functional form and data format. Also, we highlighted the climatic, developmental and risk differentials in MTE estimates.

The results showed that there is a significant increase in MTE for Iranian agriculture over the years. The research revealed that the focus of study on agronomic activities was found to be substantial. The econometric results suggest that the cross-section data generated lowest MTE estimates than other data. Besides, the stochastic frontier analysis produced higher MTE estimates than different approaches. Also, the studies focusing on the regions with a climate of cold mountain, on average, have the highest levels of MTE, while the surveys for the areas in warm and humid area climate exhibit the lowest. Additional analysis reveals that studies focusing on the regions with a low level of development and a medium level of development, on average, have less estimate of MTE, while the reviews for the areas with a high level of development have the highest MTE. Studies that have used the high-risk areas data are found to produce lower MTE score. The results of this study indicate that the robust regression especially S regression have high power to explain the variation in MTE than OLS and two limit Tobit. As regards, we suggest that researches use robust regression for the analysis of technical efficiency in future studies.

References

Aigner D, Lovell CK, Schmidt P (1977) Formulation and estimation of stochastic frontier production function models. J Econ 6(1):21–37

Aldaz N, MillÁN JA (2003) Regional productivity of Spanish agriculture in a panel DEA framework. Appl Econ Lett 10(2):87–90

Amemiya T (1973) Regression analysis when the dependent variable is truncated normal. Econometrica 15:997–1016

Assaf AG, Josiassen A (2016) Frontier analysis: a state-of-the-art review and meta-analysis. J Travel Res 55(5):612–627

Bravo-Ureta BE, Solís D, López VHM, Maripani JF, Thiam A, Rivas T (2007) Technical efficiency in farming: a meta-regression analysis. J Prod Anal 27(1):57–72

Brümmer B, Glauben T, Lu W (2006) Policy reform and productivity change in Chinese agriculture: a distance function approach. J Dev Econ 81(1):61–79

Charnes A, Cooper WW, Rhodes E (1978) Measuring the efficiency of decision making units. Eur J Oper Res 2(6):429–444

Dandekar VM (1986) Agriculture, employment and poverty. Econ Polit Weekly 21:A90–A10

Djokoto JG, Srofenyo FY, Arthur AAA (2016) Technical inefficiency effects in agriculture—a meta-regression. J Agric Sci 8(2):10

Gardner EH (2003) Creating employment in the Middle East and North Africa. International Monetary Fund, Washington

Han X, Wang L, Wang H, Wang S (2014) Efficiency evaluation of agricultural informatization based on CCR and super-efficiency DEA model. In: In International Conference on Computer and Computing Technologies in Agriculture. Springer, Berlin, pp 240–246

Iliyasu A, Mohamed ZA, Ismail MM, Abdullah AM (2014) A meta-analysis of technical efficiency in aquaculture. J Appl Aquacul 26(4):329–339

Iršová Z, Havránek T (2010) Measuring bank efficiency: a meta-regression analysis. Prague Econ Pap 19(4):22–38

Khan A, Huda FA, Alam A (2010) Farm household technical efficiency: a study on rice producers in selected areas of Jamalpur district in Bangladesh. Eur J Soc Sci 14(2):262–271

Kiadaliri AA, Jafari M, Gerdtham U-G (2013) Frontier-based techniques in measuring hospital efficiency in Iran: a systematic review and meta-regression analysis. BMC Health Serv Res 13 (1):312

Kolawole O (2009) A meta-analysis of technical efficiency in Nigerian agriculture. In: International Association of Agricultural Economists Conference, Beijing, China, August, 16–22

Kumar S, Singh MK, Meena RS, Hingonia K (2017) Influence of crop geometry and cultivars on growth, yield and production efficiency of dry direct-seeded rice (*Oryza sativa* L.). J Appl Nat Sci 9(4):2469–2476

Liu Z, Zhuang L (2000) Determinants of technical efficiency in post-collective Chinese agriculture: evidence from farm-level data. J Comp Econ 28(3):545–564

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319(5863):607–610

Mareth T, Thomé AMT, Cyrino Oliveira FL, Scavarda LF (2016) Systematic review and meta-regression analysis of technical efficiency in dairy farms. Int J Prod Perform Mang 65 (3):279–301

McDonald J (2009) Using least squares and tobit in second stage DEA efficiency analyses. Eur J Oper Res 197(2):792–798

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena RS, Gogoi N, Kumar S (2017) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359

Meena RS, Mitran T, Kumar S, Yadav GS, Bohra JS, Datta R (2018) Application of remote sensing for sustainable agriculture and forest management. Inform Proc in Agric 5:295–297. https://doi.org/10.1016/j.inpa.2018.03.003

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Minviel JJ, Latruffe L (2017) Effect of public subsidies on farm technical efficiency: a meta-analysis of empirical results. Appl Econ 49(2):213–226

Moreira López VH, Bravo-Ureta BE (2009) A study of dairy farm technical efficiency using meta-regression: an international perspective. Chil J Agric Res 69:214–223

Mugera A, Ojede A (2014) Technical efficiency in African agriculture: is it catching up or lagging behind? J Int Dev 26(6):779–795

Mulwa R, Emrouznejad A, Muhammad L (2009) Economic efficiency of smallholder maize producers in Western Kenya: a DEA meta-frontier analysis. Int J Oper Res 4(3):250–267

Najafi B (2003) Financial valuation and risk factors of industrial livestock insurance in Iran. In: Proceedings of the 2nd Scientific Conference on Agricultural Insurance, Tehran. (in Persian)

Nowak A, Kijek T, Domańska K (2015) Technical efficiency and its determinants in the European Union agriculture. Agric Econ 61(6):275–283

Odeck J, Bråthen S (2012) A meta-analysis of DEA and SFA studies of the technical efficiency of seaports: a comparison of fixed and random-effects regression models. Trans Res Part A: Policy and Prac 46(10):1574–1585

Ogundari K (2013) The paradigm of African agricultural efficiency, 1967–2012: what does meta-analysis reveal? In: 2013 Conference, August 28–30, 2013. New Zealand Agricultural and Resource Economics Society, Christchurch, NZ

Ogundari K (2014) A meta-regression analysis of frontier efficiency estimates from Africa. In: 2014 annual meeting, july 27–29, 2014. Agricultural and Applied Economics Association, Minneapolis, MI

Ogundari K, Brümmer B (2011) Technical efficiency of Nigerian agriculture: a meta-regression analysis. Outlook Agric 40(2):171–180

Ogundari K, Amos T, Okoruwa V (2012) A review of Nigerian agricultural efficiency literature, 1999–2011: what does one learn from frontier studies? Afr Dev Rev 24(1):93–106

Păun G, Mațoschi-Cîmpan O, Păun-Ciobanu MC (2012) Economic efficiency in agriculture. Qual-Acc Success 13

Rousseeuw PJ, Leroy AM (2005) Robust regression and outlier detection. Wiley, Hoboken

Song Z-J, Xu Y-Q, Zhang Z-Y (2008) A DEA efficiency analysis of chinese agriculture [J]. J Chongqing Univ (Social Science Edition) 3:24–29

Susanti Y, Pratiwi H (2014) M estimation, S estimation, and MM estimation in robust regression. Inter J Pure Appl Math 91(3):349–360

Thiam A, Bravo-Ureta BE, Rivas TE (2001) Technical efficiency in developing country agriculture: a meta-analysis. Agric Econ 25(2–3):235–243

Tobin J (1958) Estimation of relationships for limited dependent variables. Econometrica 26:24–36

Verardi V, Croux C (2008) Robust regression in Stata. Stata J 9(3):439–453

Zhang W (2015) The analysis of the agriculture input and output efficiency based on DEA model. Agric Sci Tech 16(2):414

Agrochemicals Impact on Ecosystem and Bio-monitoring

11

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Abstract

Nowadays the use of agrochemicals for agricultural farming had become inevitable towards catering the growing demand for agricultural products. Since, from the origin of green revolution the production, marketing, and use of agrochemicals had increased several folds. Only in the later years of the nineteenth century, the adverse impact of agrochemicals on the environment and human health came into light. On realizing the detrimental impacts of the overuse of agrochemicals, efforts were made to assess its toxicity to the environmental components including humans. Under this preview, this chapter describes the source and global distribution of agrochemicals in terms of its production and consumption across the world. The impact of these agrochemicals with special reference to pesticides were reviewed through their bioaccumulation and biomagnification of its residues across different trophic levels of the agroecosystem affecting the major environmental components such as air, water, and soil. Besides the residual effects on the non-targeted organisms like earthworms, fishes, birds, and humans were discussed. Humans the top predators of the agroecosystems are the worst affected due to the improper and indiscriminate use of agrochemicals, especially pesticides. Under this context exposure of humans to agrochemicals through the environment, occupation, and unexpected accidents were discussed to understand its impact on human health. Besides, the acute, sub-acute, and chronic toxic effects of pesticides were reviewed based on the recent studies conducted across the world. To understand the impact of agrochemicals on the environment, the conduct of bio-monitoring study becomes imperative, through which the risks posed by the chemicals can be assessed. The principle of bio-monitoring studies along with risk assessment and management strategies and enlisting of ecotoxicological databases were provided to better understand the adverse impact of agrochemicals on the environment and human health with further perspectives.

Keywords

Agrochemicals · Impact on ecosystem · Human health · Bio-monitoring · Risk assessment

Abbreviations

AChE	Acetylcholinesterase
BChE	Butyrylcholinesterase
DDT	Dichloro diphenyl trichloroethane
DNA	Deoxyribonucleic acid
ECOTOX	Ecotoxicology
OCPs	Organochlorine pesticides
PD	Parkinson's disease
PPE	Personal protective equipment
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
US	United States
USEPA	United States Environmental Protection Agency

11.1 Introduction

Agrochemicals are a group of different chemicals used for agriculture and its related activities. These chemicals or compounds comprise pesticides, chemical fertilizers, growth-promoting substances, soil stimulants, feed additives, veterinary drugs, etc. (Gupta 2019). Agrochemicals play a crucial role in increasing agricultural production, balancing and maintaining the soil nutrients and soil health towards protecting the crops from the infections and thereby increasing the yield to manifolds. Large quantities of agrochemicals were used in the past to increase food production for the growing global population (Meena et al. 2020b). In other words, in most of the developing countries, these agrochemicals played a significant role in the success of the green revolution, where a production level had reached several times higher than earlier (Abhilash and Singh 2009). By the year 2050, the world population is expected to reach 9.3 billion from the present status of 7.2 billion (FICCI 2016; Meena et al. 2016, 2017). This population rise will lead to a highly increased demand of agrochemicals for food and feed.

Hence, a sustainable approach is required for global food demand. Under this context, the use of agrochemicals becomes inevitable. Therefore, there is a critical challenge ahead of farmers, and thus agrochemicals have an increasing role to play (FICCI 2016). The high efficiency and user-friendly nature of chemicals and its benefits are the significant factors contributing to its market growth. Despite this, issues of global food security also impose a steady demand for agrochemicals. However, the toxicity of these agrochemicals to the environment and human health remains challenging (Mordor Report 2019). Any agricultural activity that relies on agrarian chemicals or fertilizers is often assessed based on their economic efficiencies and benefits through increased yield with reduced costs. However, decidedly less attention is given to their potential environmental effects (Udeigwe et al. 2015).

Generally, use of pesticides increases the crop yield by killing the pests, insects, and weeds, thereby preventing or reducing the plant diseases. On the other hand, fertilizer application can provide a variety of nutrients required by the soil for the growth of crops and increased yield (Jangir et al. 2016; Kakraliya et al. 2017; Meena et al. 2020a; Varma et al. 2017). Other agrochemicals such as growth-promoting hormones, soil stimulants, feed additives, veterinary drugs are also used extensively for agriculture, its related farming activities, livestock rearing, and other allied activities with the primary notion of increased production with lower costs (Zhang et al. 2018). As a consequence, varying levels of agricultural chemicals were reported in many countries in air, water, soil, food products and in human tissues (Dhananjayan et al. 2012a; Socorro et al. 2016; Alvarez et al. 2017; Raherison et al. 2018) with alarming levels. The agricultural chemicals have caused even more severe effects in developing countries, which is evidenced through several kinds of research carried out to assess the impact of agrochemicals on the environment (Tunstall Pedoe et al. 2004). Under this preview, the present chapter review gives details on the classification and use of agrochemicals, its bioaccumulation and biomagnification in the ecosystem, its environmental impacts and human exposure and health effects. Besides, the bio-monitoring and risk assessment, details on agrochemicals were also discussed.

11.2 Classification of Agrochemicals

In general, based on their intended use, the agrochemicals are broadly classified into plant protection chemicals (pesticides); plant growth-promoting chemicals (fertilizers); plant growth regulating chemicals (plant hormones, stimulants, retardants, and additives), and other allied chemicals (feed additives, antibiotics, veterinary drugs, etc.) (FICCI 2019). The use of various agrochemicals is significant at different stages of plant growth and its protection from multiple infections caused by living organisms. Besides, certain chemicals are also required in smaller quantities to enhance or stimulate or to control the plant growth, to stimulate and maintain the availability of nutrients in the soil. Apart from these, the chemicals used as nutrient additives in animal feed, antibiotics, and veterinary drugs are also finds its way into the list of agrochemicals (Gupta 2019).

As illustrated in Fig. 11.1, among the agrochemicals, plant protectors/pesticides are those chemicals that protect crops from diseases, infections caused by insect pests, and other disease-causing biological factors. These plant protecting compounds are commonly termed as pesticides which are further classified into herbicides, insecticides, algicides, fungicides, rodenticides, nematicides, molluscicides, etc. based on its target of action (Dhananjayan et al. 2020a). Plant growth-promoting chemicals are referred to as fertilizers. These are inorganic materials with a definite composition of essential plant nutrients such as nitrogen, phosphates, and potassium. Fertilizers are usually applied to the soil to make it nutrient-rich and available to the plants (Sharma et al. 2019a).

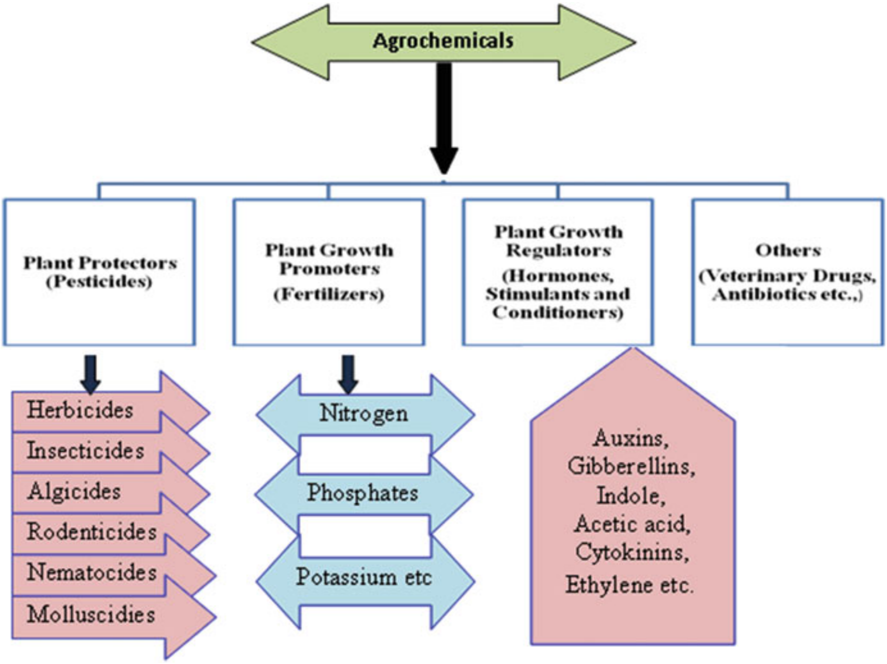

Fig. 11.1 Classification of Agrochemicals

Along with essential nutrients, micro and macronutrients required for the plants can also be made available by applying fertilizers to the soil or by directly spraying on the crop foliage (Jangir et al. 2017; Kumar et al. 2017a, b, c). Plant growth regulators are the chemicals which are synthesized biologically, mostly from plant sources and used for regulating its growth. These compounds include auxins, gibberellins, indole acetic acids, cytokinins, ethylene, abscisic acids, etc. Other miscellaneous agrochemicals contain feed additives (vitamins, amino acids, fatty acids, minerals, and steroids), cattle feed antibiotics (aminoglycosides, β-lactam compounds, chloramphenicol, fluoroquinolones, glycopeptides, etc.), and veterinary drugs (marbofloxacin, maropitant, mavacoxib, medetomidine, and meloxicam) which are used for rearing cattle and livestock as an alliance to agricultural activities (Singh et al. 2019).

11.3 Agrochemicals Usage Pattern

According to 2016 statistical report, the worldwide agrochemical market was 215.2 billion US (United States) dollars, which is expected to increase up to 308.9 billion US dollars in 2025 (https://www.statista.com). Sulfur compounds were the earliest known use of agrochemicals by Sumerian farmers during 2500 B.C. to reduce insect populations. The historical review states that, about 3200 years ago, Chinese used mercury and arsenical compounds for controlling body lice (Unsworth 2010). Initially, the chemical compounds were used for controlling plant diseases and infections. In later years the synthesis of fertilizers was invented which evolved towards the production of large quantum of agricultural fertilizers. The other group of agrochemicals such as growth regulators, feed additives, and other veterinary drugs and antibiotics came into use in the late nineteenth century (Ronquillo and Hernandez 2017). Under this context, the term agrochemical mainly comprises and considered to pesticides and fertilizers.

The global fertilizer demand for the year 2020 is around 190 million tonnes which comprise 56% of nitrogenous, 24% of phosphatic, and 20% of potash fertilizers. The demand is also expected to rise by around 200 million tonnes in 2022 (FAO 2019). The larger level of spatial and temporal variations exists in the usage of the pattern of chemical fertilizer across the world. According to a report by International Fertilizer Association (IFA), South Asia, Latin America, Africa, East Europe, and Central Asia would account for 33, 24, 15, and 12%, respectively, of the projected increase in global fertilizer demand between 2019 and 2023 (IFA 2019). Land and soil management practices primarily relay on agricultural fertilizer that has progressed the increased crop yield and soil fertility (Tilman et al. 2002). While green revolution dramatically increased the production and consumption of fertilizer for raising crop productivity (Erisman et al. 2008).

Traditionally, farmers rely on the conventional method of agricultural practices on the use of agrochemicals to control a variety of pests. The generalized use of pesticides in agriculture leads to the contamination of soil and other associated environmental resources. The persistence of pesticide residues in the soil is identified as a significant threat for soil living organisms that are supporting a key number of ecosystem services (Thiour-Mauprivez et al. 2019; Meena et al. 2020b). A multi-residue analysis method developed for the simultaneous determination of various chemicals showed that plant growth regulators and pesticides are widely used in the cultivation of medicinal plants. The high levels of pesticide residue and growth regulators were also detected in traditional medicines with high frequency (Luo et al. 2019). Though some countries have reported a declining trend of pesticide use, still it is a difficult task for many developing countries. In general, the developed countries tended to use low-toxic/low-residual pesticides, herbicides, and biopesticides, and the developing countries tended to use highly toxic chemical pesticides for crop protection.

11.4 Sources and Distribution of Agrochemicals

11.4.1 Production and Consumption of Agrochemicals

Agricultural practices and operations involve the increased use of agricultural chemicals, particularly pesticides and fertilizers, which are expected to increase the farm yield and therefore, the economical return. It has gradually led to indiscriminate and overuse of agrochemicals. However, their potential environmental effects are least concerned (Udeigwe et al. 2015). Mishandling of agrochemical constitutes one of the most several farm operation hazards dealing with farmers and the natural environment. Undesirable application time and duration, dosage, unawareness of safety precautions, and the use of contaminated or expired chemicals have been shown to impact on various ecosystems including human (Tekwa et al. 2010). As mentioned in the previous sections, among the various agrochemicals, fertilizers and pesticides are used indiscriminately in alarming levels which in turn subsequently finds its way into the environment. Once applied, these chemicals interact with all the abiotic and biotic components of the environment and cause harmful effects. On considering different varieties of agrochemicals, pesticides occupy a foremost portion of the total of agrochemicals used globally. Annually about more than two million tonnes of pesticides are used worldwide (Sharma et al. 2019b). The consumption pattern of pesticides has risen substantially in developing countries to meet the fastest growing world economy. Nearly one-third of the agricultural produce is produced with the help of pesticide usage globally (Zhang et al. 2011). Without pesticide use, the loss of fruits, vegetables, and cereals from pest injury may reach 78, 54, and 32%, respectively (Cai 2008). Crop loss from pest injury declined by 35% to 42% when pesticides were used (Pimentel 1997). The use of other pesticides accounted for the most proportion of total pesticides (53.8%), followed by herbicides (25.1%), and then fungicides and bactericides (12.1%), insecticides (7.5%), plant growth regulators (1.24%), etc. (Zhang 2018).

11.4.2 Distribution of Agrochemicals in the Environment

The increase in agricultural productivity is generally associated with the use of agrochemicals (Ismael and Rocha 2019). The consumption of pesticides increased to several folds in recent years, which had resulted in severe environmental issues. The excess quantity of fertilizers remaining after absorption by plants, further get transferred to the other environmental components such as air and water through volatilization and runoff processes, respectively. Increased amounts of nitrates and phosphates get accumulated in the irrigated agricultural land of the arid and semiarid regions, on evaporation of the irrigated water from the soil. This type of accumulation varies significantly with the depth of the soil. In the soil, the nitrogenous fertilizers get converted to nitrate through nitrification by microorganisms. Due to the negative charge of nitrates, it can easily reach underground water. In ideal conditions, plants use only 50% of nitrogenous fertilizers applied to the soil, around 2–20% of the applied fertilizer is lost through evaporation, and 15–25% of it reacts with organic compounds (Korkmaz 2007).

Several studies have reported the various techniques to improve the water retention capacity of soil and environment-friendly controlled release of agrochemicals (Saruchi Kumar et al. 2019). It is being noted that agrochemicals were detected in various environments matrixes across the world (da Costa Chaulet et al. 2019). The contamination potential of groundwater and surface water by agrochemicals applied region showed a tendency of more than 50% contamination (Ismael and Rocha

2019). Therefore, several such studies obligated the need for the implementation of environmental monitoring programs and protection measures to human health.

The common source of nitrate pollution in groundwater and surface water is the use of nitrogenous fertilizers for agriculture. Nitrate concentrations in groundwater are higher, shortly after the farming periods (Akoto and Adiyiah 2008). Eutrophication occurring in the oxygen-free bottom layer of the water body makes it unsuitable for drinking, reduces the number of living species in the aquatic environment, induces fish death, proliferates the growth of unwanted species, generates noxious odor, and makes the water body unsuitable for recreation purposes (Sonmez et al. 2008).

The extensive, indiscriminate uses of pesticides in agriculture and for other public purposes have resulted in accumulation of residues in all the components of the environment. Further to the application, the distribution, transport, and fate of different kind of pesticides are multitudinous and are very complex to assess its effects. The residues of pesticides applied in intensive agricultural areas were found in remote, pristine regions indicating its atmospheric drift, extended range of transport, and its environmental persistence. Residues of many organochlorine pesticides (OCPs) were detected in almost all environmental matrices like water, sediment and fish (Muralidharan et al. 2009; Dhananjayan et al. 2010a; Jayakumar et al. 2019), stormwater (Masoner et al. 2019), rainwater (Quaghebeur et al. 2019), and snow (Khairy et al. 2017; Lebedev et al. 2018).

11.4.2.1 Pesticides in Soils

Most of the pesticides used for agricultural activities and other purposes get accumulated in the soil after application. The accumulation of pesticide residues is increased by the discriminate and repeated use of pesticides. The edaphic factors and soil microbial diversity decides the fate of the applied pesticides in the soil as it may undergo degradation, adsorption, or transport to other regions (Hussain et al. 2009). The indigenous microbes in the soil are affected by the degradation products of the pesticides. These degradation processes affect the microbial diversity, enzyme production, and biochemical reactions of the microbes in the soil. (Hussain et al. 2009; Munoz-Leoz et al. 2011). This, in turn, leads to soil infertility (Handa et al. 1999). Several studies have highlighted the impact of pesticide residues on soil microbes (Sofo et al. 2012). Besides this, the growth, colonization, and metabolic activities of arbuscular mycorrhizae, root colonizing microbes, and few species of algae and fungi were also found to get disturbed by the persistent pesticide residues (Tien and Chen 2012).

The excessive use of pesticide residues in soil inhibits the growth or kills the microbial population in soil (Hussain et al. 2009). Xie et al. (2011) reported that pesticide application had reduced the fungal biomass by 47% and bacterial biomass by 76% on average after 9 days of application. It has also been stated that the biochemical activities in the soil like nitrogen-fixing, nitrification, and ammonification are induced and catalyzed by soil microbes is affected by pesticide residues. Moreover, the antagonistic effects of the microbes with soil are influenced by the pesticide residues (Sebiomo et al. 2011; Srinivasulu et al. 2012).

In general, soil comprised of free enzymes are collectively referred as enzymatic pool that serves as the indicator for soil fertility and quality (Hussain et al. 2009). Degradation of both pesticides and natural substances in the soil is mainly catalyzed by this enzymatic pool (Floch et al. 2011). Hence, the impact of pesticides on soil biological functions can be conveniently quantified by measuring the change in the enzymatic activity of the soil (Garcia et al. 1997; Romero et al. 2010). Many studies have indicated the changes in activities of soil enzymes like dehydrogenases, oxidoreductases, and hydrolases due to pesticide accumulation in soil (Megharaj et al. 1999).

The bioavailability and degradation of pesticides depend on many environmental factors like soil organic matter, its texture, vegetation type, and cultivation practices (Murage et al. 2007). As water acts as a solvent for pesticide movement and diffusion and is essential for microbial functioning, the levels of soil moisture act as the most important factors that regulate pesticide bioavailability and degradation (Pal and Tah 2012; Camargo et al. 2013). So, monitoring the effect of pesticides on soil microbes is essential to assess its deleterious effects.

Soil samples collected at different parts of China were found to have mean pesticide residues of about 2861 μg kg^{-1} (micrograms per kilogram) due to indiscriminate use of agrochemicals. Besides the residue levels were also found to be very dynamic and expected to cause potential health risks (Yu et al. 2020). An extensive study conducted by Silva et al. (2019) revealed the presence of 76 pesticide residues in 317 agricultural topsoil samples collected across the European Union. Similarly, soil samples collected during post-harvest periods, across the southern districts of Jordan was found to have a high quantity of pesticide residues (Khailani et al. 2019). An extensive review on organophosphorus insecticides also reported the ubiquitous presence of its residues in water bodies surrounding the agricultural regions in most of the developing countries (Sidhu et al. 2019; Climent et al. 2019). Subsequently, the uncontrolled application of pesticides along with its detrimental impacts on the environment is also on the rise across the globe (Rodríguez and León 2020). Thus, from the review of the above studies, it was clear that the effect of pesticides residues in soil should be viewed with grave concern.

11.4.2.2 Pesticides in Air

Besides causing water and soil pollution, use of agrochemicals also disturbs the atmosphere. Several air monitoring programs globally have ensured the presence of pesticide concentrations even in far off places from where it has been applied. Organochlorine pesticides were banned or restricted for use after the 1960s in most of the developing and developed countries due to their persistence and bioaccumulative nature. Later, the second, third, and fourth generation pesticides like organophosphates, carbamates, and pyrethroids were extensively used for pest control (Kumar et al. 2012). However, all these pesticides were found to be toxic. Further neonicotinoid insecticides were introduced in the 1990s after laboratory and field testing determined that they were safe to non-target organisms. However, their contamination and toxicity issues were still in debate (Mancini et al. 2019). Although, agricultural pesticides have a vital role in feeding a rapidly growing human population (Godfray et al. 2010), but their use has significant consequences for the environment (Kumar et al. 2012).

The OCPs, naturally possess high environmental persistence and bioaccumulating potential and are prone to long-range transportation (Taiwo 2019). These OCPs contaminate water, air, and soil through multiple routes (CDC 2016). Due to their environmental persistence and a long range of transport, their presence was reported even in very remote location (Hung and Thiemann 2002; Huang et al. 2019). Among numerous types of OCPs, only very few are volatile, while most of them may stick to soils or particles in the air (Samaranda and Gavrilescu 2008). Persistent organic pesticides monitored in urban and rural sites along the coastal region of India also reported their widespread occurrence. Presence of dichloro diphenyl trichloroethane (DDT), hexachloro cyclohexanes, and chlordane in the air is due to the various factors and the volatility or semi-volatility nature of the pesticides imparts the atmospheric pollution (Zhang et al. 2008).

It has been stated that the OCPs that have been used historically to the agricultural soils experience long term transport into the atmosphere and were even found as residues in urban air also (Qu et al. 2019). The primary source of agrochemical residues in the air is due to its atmospheric drift and volatilization rather than resuspension from soil particles (Ravier et al. 2019). Wang et al. (2019) reported the presence of residues of around 14 current use pesticide residues and 21 historically used OCPs in the air samples collected around Costa Rica city indicating the ubiquitous presence of pesticide residues in the atmosphere. A study reported the presence of organo-thiophosphate insecticides residues, especially chlorpyrifos in the air of Arctic region, which is due to long-range transport of these chemicals from the point and non-point sources (Anjum et al. 2017). Quality of air is measured through the number of pollutants, including agrochemicals (Socorro et al. 2016). Agrochemicals have the potential to contaminate our air, affecting human, animal, and plant health (Tsai et al. 2019). The perusal literature showed air pollution and agrochemicals were associated with an adverse effect on children in Asian continents (Tsai et al. 2019; Raherison et al. 2018).

A large volume of applied pesticide is getting volatilized directly into the air within a few hours to few days of application. Very few studies in recent years have reported the occurrence of pesticide residues in the air (Woodrow et al. 2018; Raherison et al. 2018). However, it has been advocated that more systematic and continuous assessment studies are required to understand the presence, transport, and fate of pesticide residues in the atmosphere (Dhananjayan et al. 2020a). Hence, from the glimpse of several studies reviewed, it was evident that the agrochemicals applied for agricultural activities experience a comprehensive and extended range of transport and occurs as residues in air and contaminates the atmosphere as a whole due to its persistent nature.

11.4.2.3 Pesticides in Water

Similar to air, pesticide contamination in water is a worldwide concern. Various statutory bodies across the globe have conducted studies to regulate the concentrations of pesticides in drinking water in order to reduce the risk to human health (Sjerps et al. 2019). Pesticide residues reach water bodies through agricultural runoff, spillage from point sources, cleaning of spray equipment, etc. (Singh and Mandal 2013). Rainfall and irrigation practices also trigger the runoff of pesticide residues into the water bodies (Larson et al. 2010). World Health Organization had listed 48 active pesticide ingredients and the United States Environmental Protection Agency (USEPA) had listed 21 pesticides and their related products, as toxic contaminants in their Drinking Water Quality Guidelines and national Primary Drinking Water Regulations, respectively (USEPA 2009). It was found that OCPs enter into the water bodies mainly through runoff and leaching from agricultural farmland/soil, domestic sewage and industrial effluent discharges, and atmospheric deposition (Yang et al. 2005). Several recent investigations on OCP residues highlighted the occurrence and accumulation of OCPs residues in various environmental components (Behfar et al. 2013).

The water samples collected from Rawal Lake, of Pakistan, the primary source of drinking water to nearby regions, was found to contain 4-time higher levels of residues of pyrethroids pesticides than the standards levels. The occurrence of residues in the lake was mainly attributed to runoff contamination from nearby agricultural regions (Khan et al. 2020). It has also been stated that rising temperatures across the globe favor the predominant occurrence of agrochemical residues in water bodies. Evidence of agrochemical increase in concentration levels during summer season attributes to the trend of its contamination in water bodies (Das et al. 2020). It has been stated that the traces of pesticide residues in the atmosphere can lead to contamination of surface water system through wet precipitation and increase moisture conditions in the atmosphere (National Pesticide Information Centre -NPIC 2016). A review by Dereumeaux et al. (2020) clearly explained that most of the residents living nearby the agricultural lands are exposed to pesticide residues through the water sources in their vicinity. A study by Tang et al. (2014) reported that one of the major factors attributing to the higher carcinogenic risk to humans is the contamination of drinking water sources with pesticide residues. Thus, the agrochemicals applied to increase the agricultural productivity find its way into the aquatic environment and results in residue accumulation leading to the detrimental effects over the environment.

11.5 Impact of Agrochemicals on Ecosystem

11.5.1 Bioaccumulation and Biomagnification

Bioaccumulation refers to the accumulation of a chemical in the tissues of an organism throughout its life. When the chemical concentration gets increased among the organisms from one trophic level to the other in a food chain, then it is referred to as biomagnification (Fig. 11.2). These two processes coincide in any ecosystem when the presence of chemical residues in the environmental matrices of the habitat exceeds the limit. This results in accumulating residues within the

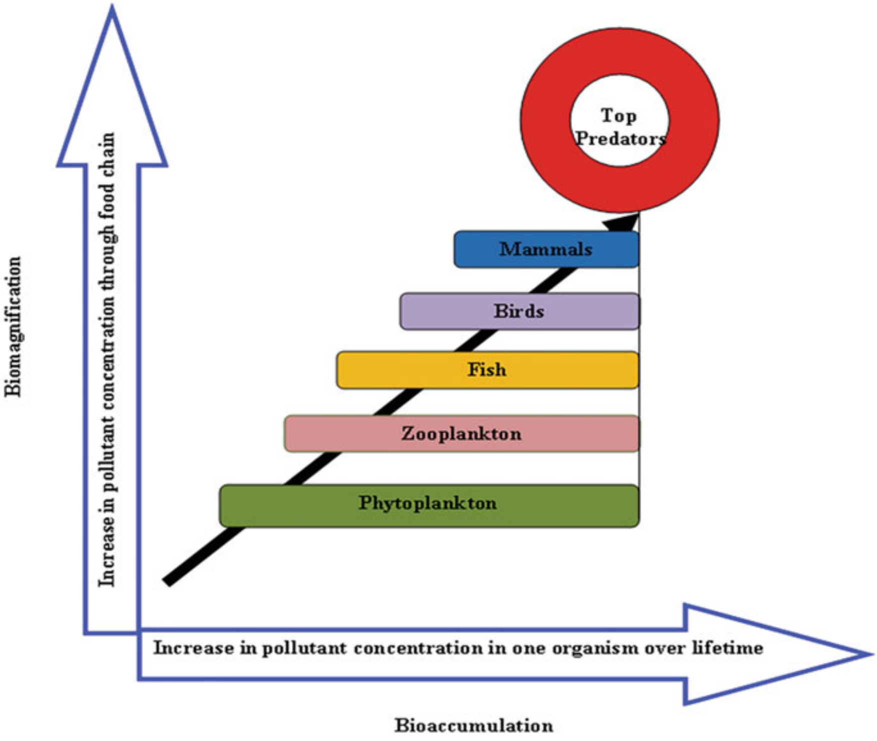

Fig. 11.2 Bioaccumulation and biomagnifications process in the natural ecosystem

organisms which in turn gets transferred to the next trophic level and gets biomagnified to very toxic levels (Gobas et al. 2009).

This process happens in any environment due to the high persistent nature and longer half-life of the chemicals. Concerning agrochemicals, pesticides are known for its environmental persistence whose half-life in soil, air, and water ranges from a few hours to several years.

Bioaccumulation and biomagnification play a significant role in any bio-monitoring and risk assessment study. Several efforts were taken by many countries based on the Stockholm Convention on persistent organic pollutants, to regulate the use, manage the distribution, and to assess its environmental and health effects. In particular Toxic Substances Control Act (USEPA 1976) in the USA, Canadian Environmental Protection Act in Canada (CEPA 1999), and the Registration, Evaluation, Authorisation and Restriction of Chemicals program (REACH) were most prominent in establishing the regulations for the use of persistent chemicals. However, such rules were not available in specific for developing countries and underdeveloped countries, where a very little knowledge of bioaccumulation and biomagnification pattern of persistent agrochemicals is available.

Researchers are very much concerned from long back, on the extensive and historical use of chemical fertilizers. Their indiscriminate use had also led to the accumulation of toxic heavy metals in the soil. The leachate from the agricultural fields enters the water body, thereby accumulating the heavy metals in water bodies also. Later the process of biomagnification occurs across the food chain in terms of heavy metal residues. In particular, the bioaccumulation and biomagnification of metal residues like arsenic and cadmium occur in most of the soils and water bodies. A study by Lenka et al. (2016) showed the accumulation pattern of metal residues, their biomagnification pattern leading to the health effects to humans due to the overuse of phosphatic fertilizers for a long period.

A few other studies have reported that the residues of heavy metals have increased several folds beyond the standard limits due to the increased use of fertilizers for agricultural purposes. Similarly, pesticide residues in almost all the environmental matrices were reported (Zhou et al. 2015). Studies on bioaccumulation and biomagnification of agrochemical residues advocate that the persistent nature of these chemicals in soils are influenced by several factors like its physical and chemical properties, atmospheric temperature, chemical nature of the compound, uptake efficiency by the crops, and interactive properties of the compound with the soil air and soil water (Adhikari et al. 2012). Therefore, adequate knowledge of the factors influencing the environmental effects of bioaccumulation and biomagnification pattern of agrochemical is necessary.

11.5.2 Soil Ecosystem

The first and foremost component exposed to the agrochemicals is the soil system rather than the target crops or plants. The process of bioaccumulation and biomagnification starts from the soil component. The magnitude of bioaccumulation and biomagnification of any agrochemical is directly proportional to its persistent nature and lipophilic nature. Based on this observation, it was evident that organochlorines persist for a longer time in the soil when compared to organophosphate compounds (Favari et al. 2002). Thus, to assess the effect of agrochemicals on soil, bioaccumulation and biomagnification studies become necessary. Moreover, further studies have to be carried out before the commercial use of these chemicals for agricultural purposes. In most of the cases, these agrochemicals are used indiscriminately beyond its requirement, which naturally enhances the rate of accumulation and magnification. Besides these residue levels surpass the carrying capacity of the soil and pose a significant threat to soil microflora and macro soil fauna (Thiour-Mauprivez et al. 2019). Hence the foremost analysis in any bioaccumulation or biomagnification study happens to be the assessment of chemical residue in the soil component. Several new technologies have risen recently to understand the nature of the bioconversion processes clearly. One among them is the use of isotopes of carbon and nitrogen as additives or fortified along with commonly used agrochemicals. The pathway and concentration of these labelled isotopes are analyzed and assessed for its bioaccumulative or biomagnifying property across the trophic levels in the ecosystem (Borgå et al. 2011). Besides several modelling studies, simulation studies reveal the process of bioaccumulation and biomagnification in the soil ecosystem.

11.5.3 Non-Target Organisms

The pesticides applied for agricultural purposes over a long time have affected the non-targeted organisms. Worldwide many reports had documented the toxic effects of pesticides to the non-targeted organisms like arthropods, fishes, amphibians, and human (Ware 1980). When these agrochemicals are applied to the agricultural fields for preventing or controlling pathogenic pests, the most affected are the natural insects and parasites, which help in pollination and natural predation (Vickerman 1988). Due to the indiscriminate use of pesticides, the population of other soil invertebrates such as nematodes, mites, earthworms, spiders, and soil microbes gets dwindled and disturbed. These organisms play a significant role in the decomposition of organic matter from plant debris, maintain the soil structure, and help in the transformation and mineralization of plant nutrients. Only these groups of organisms make the soil healthy by conditioning them with their metabolic activities and also ensure the bioavailability of nutrients to the soil. Due to these activities, the food web patterns of the agricultural gets balanced and maintained (Hill and Garg 2014). Hence the impact of overuse of agrochemicals on the non-targeted organisms in terrestrial and aquatic ecosystems should be given its due importance. Under this context, a detailed review of the impact of agrochemicals on non-targeted organisms is discussed below.

11.5.3.1 Earthworms

Among the soil invertebrates, the highest proportion of the population (>80%) was represented by Earthworms (Yasmin and D'Souza 2010). Earthworms have a prominent role in maintaining the soil quality by decomposing the organic matter to humus through their metabolism and retain the moisture content of the soil. They are also responsible for soil aeration, soil particle aggregation, and agglomeration, which in turn maintain the soil structure. However, the diversity and density of earthworm population in the soil is very sensitive to soil management practices. Hence these organisms are referred to as the best indicator organisms for soil quality (Paoletti 1999). Use of pesticides is one of the significant factors which affect the earthworm population in the soil. Several organochlorine insecticides and organophosphate pesticides were found to affect the earthworm populations. Nevertheless, the use of a high quantity of agrochemicals is continued, which directly affects the density and diversity of the earthworm population in soil (Pelosi et al. 2013).

The intermittent and chronic exposure of earthworms to the chlorpyrifos, azine, and methyl carbamates residues in soil was found to be detrimental to the earthworms as per the results of the field study conducted in South Africa (Reinecke and Reinecke 2007). Several studies across the world have documented that the pesticide residues in soil have affected the growth, behavior, and reproduction of earthworms. Standardized laboratory tests also have confirmed pesticide concentrations affect the earthworms' population (Yasmin and D'Souza 2010). The detrimental effects such as body swelling, rupture of cuticle, paling and softening of the skin, and oozing out of coelomic fluid were observed in earthworms exposed to different kinds of pesticides (Solaimalai et al. 2004). It has also been stated that the extended exposure of pesticides to earthworms also results in physiological activities such as cellular dysfunction and protein catabolism and also causes neurotoxic effects (Schreck et al. 2008). However, we could observe that systematic toxicity studies on earthworms lacked in several parts of the world where overuse of pesticides was documented.

11.5.3.2 Pollinators

Pollinators refer to any biotic agent that helps for the pollination process. In general, the pollinators include the honey bees, fruit flies, beetles, and birds which indirectly help in pollination through their foraging behavior. These pollinators also act as suitable bio-indicators as these species are susceptible to environmental stress. When these organisms and their population get affected by predation, habitat alteration, and chemical residues, it directly influences the natural pollination and causes the floral population imbalance in any agroecosystems (Kevan 1999). The pesticide residues in the environmental matrices affect the foraging behavior of the pollinators and cause colony mortality, especially in honey bees. Since honey bees account for 80% of the pollinators, the effects of pesticides on honey bees have been widely reported across the world.

Neonicotinoid insecticides are presently used on vast scales across the world. These pesticides are currently being studied for their toxicity profile. It has been reported that these pesticides have a high potential for leaching into the surface and groundwater environments from the soil and has been detected frequently in water bodies at the vicinity of agricultural regions across the world (Bonmatin et al. 2014). However, only a little information on the effect of pesticides on non-targeted invertebrate species is available. Several findings have documented the toxic nature of pesticides on honey bee population (Blacquiere et al. 2012). These toxicity effects include the abnormal foraging behavior, decreased learning and memory abilities of bees, lack of reproductive capacity, and reduced efficiency in pollen collection and finally results in Colony Collapse Disorder (Gill et al. 2012).

Besides these, thiamethoxam, a neonicotinoid insecticide was reported to cause non-lethal effects to honey bees by causing homing failure in honey bees which results in colony collapse (Henry et al. 2012). It has been stated that the imidacloprid residues have affected the longevity and foraging habit of honey bees, particularly in *Apis mellifera* species (Pettis et al. 2012). In a particular instance, it was observed that the microsporidia infections caused by *Nosema ceranae* in the guts of honey bees were high in imidacloprid treated bee hives resulting in colony mortality (Wu et al. 2012). There are also several studies documenting the toxicity of imidacloprid causing the reduced brood production because of decline in the fecundity of bumblebees (*Bombus terrestris*) (Whitehorn et al. 2012). In contrast, only very few studies have been conducted globally to assess the risk posed by the pesticides to the pollinator species (Brittain et al. 2010). At present, Neonicotinoids are the widely used insecticides across the world and are thus the main focus for investigating possible relationships with mortality of honey bees.

11.5.3.3 Amphibians

Amphibians are found to inhabit a variety of habitats such as fresh and marine water ecosystems, salt marshes, estuaries, and in terrestrial ecosystems mainly lands associated with agricultural activities. Amphibians are vertebrate organisms and ectothermic favoring the accumulation of chemical residues. Globally a fast decline is observed in the amphibian population, which has alerted the researchers worldwide to assess the responsible factors. It has been stated that 7.4% of the total amphibian population was listed as critically endangered, and almost more than 43% of the amphibian population is experiencing due to various factors (Stuart et al. 2004). Though several reasons were attributed to the amphibian population decline, pesticide residue accumulation was observed to be one of the main reasons. Besides, climate change and global warming also contributed to the increase in the concentration of pesticide residues in aquatic systems and had increased the impact on amphibians (Johnson et al. 2013).

Many studies expressed that, the permeable skin, rudimentary immune system, and dual habitat system of amphibians make them more susceptible to environmental contaminants (Kerby et al. 2010). The residues of most commonly used herbicide glyphosate were found to occur predominantly in most of the amphibians (Relyea 2012). Another study also reported that high mortality rate of tadpoles and juveniles was observed in three frog species of North America in the natural pond ecosystems due to the residues of commonly used organophosphate pesticide (Relyea 2005).

It has been observed that the European common frog (*Rana temporaria*) experienced 100% mortality within 1 h of exposure to recommended concentration of pesticides, whereas the mortality decreased to 40% after 7 days after application of pesticides. This demonstrates the acute toxic effects posed by the pesticide residues to the frogs (Brühl et al. 2013). However, evidence was not substantiated for their resistance to selective pesticide residues. Besides the residue accumulation in amphibians are also due to biomagnifications through their food sources such as phytoplanktons, zooplanktons, and fungi, which are their primary energy sources. Malathion sprayed to control mosquito breeding in US aquatic ecosystems bioaccumulated the residues from water sources travelling through phytoplankton, periplankton, and finally declining the population of frog tadpoles (Relyea and Hoverman 2008). Even lower concentrations of malathion were found to cause toxic effects in aquatic communities (Relyea 2012).

An investigation by Christin et al. (2013) revealed that frogs (*Rana pipiens*) in agricultural fields were found to be smaller in size and have reduced weight than the frogs surviving in comparatively less contaminated areas. This difference is due to their exposure to the high quantum of chemicals; moreover the frogs of the former category are more vulnerable to diseases and infections due to their impaired immune system. Kittusamy et al. (2014) have quantified pesticide residues in 109 frogs belonging to two species (*Fejervarya limnocharis* and *Hoplobatrachus* *crassus*) from organic and conventional paddy farms in Kerala, India and found that seven frogs from conventional but none from the organic farms revealed deformities due to high concentration of pesticide residues in their habitats. Hence, the habitat loss and exposure to pesticides are considered as the primary factors contributing to amphibian population decline in the agricultural ecosystem.

11.5.3.4 Fishes

Fishes are one of the critical and best-suited indicator organisms in both freshwater and marine ecosystems as they are interacting very closely with the physical, chemical, and biological parameters of the aquatic environment. They form a crucial link in the aquatic food chain and food web, where it feeds on phytoplankton, zooplanktons, and debris in sediments accumulating the chemical residues. Further, when sea birds and marine mammals feed these fishes, biomagnification of residues becomes intense. Wetland birds have been used as an indicator of pesticide contamination (Muralidharan et al. 2015). A lot of studies have been conducted across the world to understand the impact of agrochemical residues on fish population (Scholz et al. 2012). Pesticide residues are found to be very predominant, causing mass mortality of fishes. Many studies have documented the ill effects of pesticide residues in their growth, behavior, and reproduction. In Europe, around 27 freshwater fish species were found to contain various pesticide residues (Ibrahim et al. 2013). These residues ultimately find its way into the aquatic food web leading to biomagnification.

Among the agrochemicals used extensively in the past and present, organochlorine pesticide residues were found to get detected in almost all the studies and even exposed to get detected in the Arctic food webs, the ecosystem far off from the site of application of pesticides (Hargrave et al. 1992). Muralidharan et al. (2009) have documented the occurrence of OCPs in the commonly consumed fishes of South India impacting health effects on consumers. The study conducted by Dhananjayan and Muralidharan (2010a) also revealed the presence of organochlorine residues in the fishes of Karnataka wetlands which also found to have dietary implications. A study conducted in West Bengal revealed that tissues of carp and catfishes such as gills, liver, brain, and alimentary canal were severely affected by the pesticide residues. On analysis, these tissues were found to contain a high amount of organochlorine pesticide residues. Jayakumar et al. (2019) had documented the residues of OCPs like hexachlorocyclohexane (HCH), DDT, heptachlor epoxide, endosulfan, and dieldrin in various species of fishes in bird sanctuaries.

Many studies have reported the acute and chronic toxic effects of pesticides to the fishes. A study by Kumari (2012) said that the commercial organophosphate pesticide Abate have caused alterations in vitellogenesis of *Heteropneustes fossilis*, commonly called as catfish and had severely affected its farming. Reports also indicate that the toxic residues in fishes had led to the disruption of olfactory function in fishes which caused abnormalities in their mating behavior, predator avoidance, food preference, and community discrimination behavior, ultimately leading to its death (Tierney et al. 2010).

On the other hand, the accumulation and magnification of pesticide residues in fishes were influenced by several factors like its water solubility, half-life, uptake mechanism by the organisms, environmental persistence, etc. In most of the cases, the lipophilic nature of the pesticides favors its accumulation and magnification in fatty organisms to alarming levels. Thus when an organism is said to have a high composition of fat in their tissues, it is likely to accumulate more pesticide residues in their tissues (Pereira et al. 2013). Besides it has also been reported that temperature, alkalinity, and body size of the fishes greatly influence the toxic effect of the residues on the fishes (Capkin et al. 2006). Even it is stated that alteration in water pH caused due to the accumulation of wastes imposes an acute threat to aquatic life (Satyavani et al. 2011). Hence it is clearly understood that complex factors were involved in terms of bioaccumulation and biomagnifications of agrochemical residues in fishes.

11.5.3.5 Birds

Birds are considered as the valuable indicators in terms of chemical contamination, their residue accumulation, and magnification in the environment. Their role in the food chain and food webs is most crucial in any ecosystem. They act as predators feeding on pathogenic insects, help in pollination, and provide many types of ecosystem services. There are several instances where pathogenic infections are at a higher rate in the absence of the common bird species. Birds despite providing ecosystem are subjected to pesticide poisonings inadvertently through various routes. Accumulation of pesticide residues in various tissues of terrestrial and water birds (Dhananjayan 2012a, b, c; Muralidharan et al. 2012) and reduction of cholinesterase activity (Dhananjayan et al. 2012a) were reported across the world (Smith et al. 2010). Direct ingestion of granulated pesticides, pesticide-treated seeds, direct exposure to pesticide sprays, feeding on contaminated food and water are few of the courses, which leads to their mortality (Fishel 2013). As per USEPA, around 50 commonly used pesticides have toxic effects to almost all groups of birds like songbirds, shorebirds, seabirds, and raptors (BLI 2004).

Pesticide residues are known to cause behavioral changes and reproductive effects in birds. Several studies have documented the presence of organochlorine pesticide residues in the plasma samples of commonly occurring bird species of India (Muralidharan et al. 2008, 2012; Dhananjayan and Muralidharan 2010b; Dhananjayan et al. 2011a, b). The occurrence of pesticide residues in the birds of these studies relates the bioaccumulation and biomagnification of pesticide residues through the food chain (Dhananjayan 2013; Dhananjayan and Muralidharan 2013; Dhananjayan et al. 2020b), as explained in the previous section. Besides their studies also exposed the presence of pesticide residues in vultures which are exposed to pesticide residues through their diet (Muralidharan et al. 2008; Jayakumar et al. 2020). Many agrochemicals posing impact on birds include organochlorines, organophosphates, and carbamates. All these pesticide residues cause behavioral changes, eggshell thinning, leading to reproductive effects (Mitra et al. 2011). Boatman et al. (2004) proposed that the indirect effects of pesticides through the food chain as a possible factor for the decline in farmland bird species.

It was estimated that around 672 million birds are exposed to pesticide residues every year out of which 10% attains mortality due to acute toxic effects of pesticides (Williams 1997). Among the agrochemicals, the fungicides and insecticides exert a massive threat on farming birds commonly found in agricultural regions. In particular, the ground nest farming birds in the USA were found to be highly affected due to acute toxicity of pesticide residues (Mineau and Whiteside 2013). Hence from the above-referred studies, it was evident that the pesticide residues actively get bioaccumulated and biomagnified across the food chain and food web and cause reproductive effects and mortality of the non-targeted bird species.

11.6 Exposure to Agrochemicals and Human Health

Several research studies in the past have focussed on the vulnerability of agricultural workers to pesticides. The general population in the residential regions around the farming lands are profoundly affected due to the movement of pesticides from their intended application sites during application and post-application time. Besides this, wind erosion of soil particles, volatilization of pesticide compounds, and their atmospheric drift also causes its wide distribution to the non-targeted regions (Kubiak et al. 2008). More than half of the applied pesticides are lost without their intended action on pests due to the application methods, formulations, and environmental conditions. Beyond this, the atmospheric conditions also support their loss (Ravier et al. 2005). Many air monitoring studies exposed the presence of a high concentration of pesticide residues in the air surrounding agricultural areas, whereas their concentration levels decreased with increasing distance from the agricultural fields (Garron et al. 2009). Besides, pesticide residues were also found to occur in indoor air samples of residential regions lying nearby agricultural areas (Coronado et al. 2011). Individuals living in the vicinity of agricultural fields treated with pesticides are highly exposed to these pesticide residues, either through inhalation of, dermal contact or through precipitation, dust and ingestion of contaminated food or drinking water (Wilson et al. 2010; Kubiak et al. 2008). The harmful effects of pesticides on human health were very adverse due to their acute and chronic toxic nature and their persistence in the environment and their capability to enter into the food chain very quickly.

In general, pesticide exposure to humans through their occupation and intentional or unintentional poisoning leads to acute toxic effects (Dawson et al. 2010; Lee et al. 2011). Pesticide poisoning in simple cases may lead to many specific symptoms and it may also lead to coma and death (Pan-Germany 2012). The severity of the toxic effects depends on the quantity of the chemical used, its mode of action, mode of application, length and frequency of contact time, and person exposed during application (Richter 2002). There are about three million cases reported for acute pesticides poisoning worldwide every year. Out of these three million cases were of unintentional pesticide poisoning, two million cases were intentional suicide attempts, and the rest of them being due to occupational or accidental poisoning (Singh and Mandal 2013). Acute toxicity of pesticides leads to several suicide cases due to the widespread availability of pesticides in rural areas (Richter 2002; Dawson et al. 2010). However, some studies had shown a considerable decline in suicides via pesticide consumption in recent years (Mew et al. 2017). Many strategies have been proposed across the word to reduce the incidences of acute pesticide poisoning and self-poisoning by creating awareness in prompt use of personal protection equipment (Murray and Taylor 2000). Also, strict regulating requirements on pesticide sales along with pesticide usage and community involved awareness programs, and prudent efforts are needed to be imposed. Continued exposure of humans to pesticide even in minimal quantities for a prolonged period may result in chronic illness (Pan-Germany 2012). Among the exposed population, agricultural workers are at a higher risk. However, the general population is also affected considerably due to pesticide-contaminated food, air, and water (Pan-Germany 2012). Incidences of chronic diseases are on the rise in direct proportion with the increased use of pesticides.

Several techniques have been demonstrated to link the symptoms of chronic diseases with pesticide exposure. Interaction of pesticides with genetic materials which results in deoxyribonucleic acid (DNA) intact condition (damage) is considered to be one of the primary mechanisms that lead to the chronic diseases (Mostafalou and Abdollahi 2012). A large number of studies reported an increase in the frequency of chromosomal aberration, sister chromatid exchange, reduction in cholinesterase activity, and DNA damage in pesticide exposed population in agricultural fields (Dhananjayan et al. 2012b, 2019; Santovito et al. 2012). The health effects to humans due to pesticide exposure are explained in a further section. Hence, it is important to understand the toxic effects of pesticides in almost all the environmental components.

11.6.1 Exposure Pathways

The intensive agricultural practices in many countries have led to a significant rise in the use of agrochemicals. The huge demand for agricultural products has led to the extensive use of agrochemicals globally (Adu et al. 2019). Although it is proved beyond doubt that this has increased the agricultural productivity, still there is a rising apprehension regarding the redundant effects on the environment and the health of the population (Kudagammana and Mohotti 2018). However, the use of agrochemicals, mainly pesticides, were restricted to a greater extent in developed countries, but this is not the case with developing countries where it is still used extensively for various purposes. Pesticides and other agrochemicals irritate the skin and respiratory system in humans. Studies have shown that pesticide exposure is associated with the occurrence of asthma in adults (Baldi et al. 2014). For several decades, the relationship between environmental exposure to chemicals and allergic diseases continues to be a highly debated phenomenon. (Bloomfeld et al. 2006). When considering the personal health effects rather than fertilizers, pesticides are the persistent notorious compounds which exert dreadful impacts on exposure. Hence this section of the chapter deals with exposure to pesticides and its related health effects.

11.6.1.1 Environmental Exposure

The US National Research Council stated that 3% of developmental disabilities resulted from environmental exposure to agrochemicals (Grandjean and Landrigan 2006). The study conducted by Requena et al. (2018) proved that the occurrence of epilepsy in the study population is related to their exposure to pesticides. In other words, the higher the exposure to pesticides, the higher the presence of epilepsy which suggested that environmental exposure to pesticides might increase the risk of having epilepsy. It was reported that pesticides applied to farmlands, leading to multitudinous toxic exposure, exert additive or synergistic effects (Thiruchelvam et al. 2000). Besides these, agricultural chemicals, mainly pesticides end up in the environment as complex mixtures, and it is their combinational effects that need to be evaluated, rather than assessing the traditional single impact of the active ingredients (Horn et al. 2019). A recent review by Dhananjayan et al. (2020a) highlighted the fate of pesticides in the environment and its effects on human health, due to conventional methods of pesticide application in the agriculture field. As a result, presence of these chemicals were reported in various components of the ecosystem, including human (Dhananjayan and Ravichandran 2014). Many such results indicate the presence of pesticides even in dietary products (Muralidharan et al. 2009; Dhananjayan 2012a).

11.6.1.2 Occupational Exposure

Though, the general population is exposed to pesticides through various sources, mainly, workers in the agrochemical industry and farmers and sprayers, who are the end-users of agrochemicals, represent a high-risk group (Aiassa et al. 2019). Neglected use of personal protective equipment (PPE) among agrochemical workers and farming community leads to occupational exposure. Many studies proved that occupational exposure to pesticides increased the values of chromosomal aberrations, micronuclei, and comet assays and DNA fragmentation biomarkers. It is suggested that long term exposure to pesticides is a potential risk to workers' health (Aiassa et al. 2019). The study conducted by Requena et al. (2019) links the association between increased environmental exposure to pesticides to thyroid gland disorders, thus supporting and extending its previous evidence. Several research and review studies highlighted the occupational exposure and mental health effects among agricultural farmers (Khan et al. 2019). Chronic exposure to pesticides can damage DNA and lead to cancer, diabetes, respiratory diseases, and neurodegenerative and neurodevelopment disorders. A recent study by Dhananjayan et al. (2019) evaluated the reduced activities of erythrocyte acetylcholinesterase (AChE) and plasma butyrylcholinesterase (BChE), which acted as biomarkers of pesticide exposure and also caused genotoxicity affecting the DNA peripheral blood lymphocytes in women workers exposed to agrochemicals in tea gardens in South India. Similarly, reduced cholinesterase activities and presence of pesticide residues in blood samples of sheep wool and agricultural workers were reported in India (Dhananjayan et al. 2012a, b). Several studies have highlighted the occupational exposure and risk of farmers to agrochemicals in the agricultural field (Dhananjayan and Ravichandran 2018). The results suggest that to minimize the health risks due to occupational exposure to pesticide residues, periodic monitoring of these biomarkers along with imparting education and training is necessary. A study by Leite et al. (2019) evaluated the pesticide induced DNA damage among children of rural areas in Paraguay and highlights that the children exposed to pesticides are at a higher risk of genotoxic and cytotoxic effect compared to non-exposed children. The comet assay and micronuclei test results revealed a higher rate of genetic damage in the exposed population than in the control group (Marcelino et al. 2019).

There are growing concerns on the health status of the farming community and their exposure to agrochemicals. Regardless of their recognition and widespread use, farmers are continuously exposed to those chemicals (Soares and Porto 2009). These incidences have created a large number of poisoning cases, which has led to significant health risks to farmers both in short and the long run. In particular, farmers in developing countries face a greater risk of exposure due to these toxic chemicals that are even declared as banned or restricted to use in their countries. Inappropriate application techniques, poor maintenance, or unscientific methods of spraying are most commonly reported practices of farmers (Dhananjayan et al. 2019). Recent studies have also highlighted the conventional method of application of pesticide and agricultural practices and unawareness of newer technologies in their field (Dhananjayan et al. 2019). Additionally, workers in agriculture field practice inadequate or poor knowledge on the correct application and the necessary precautionary measures (Recena et al. 2006). At the same times, even farmers those who are well aware of the harmful effects of pesticides are unable to implement their awareness into their practices (Isin and Yildirim 2007; Zyoud et al. 2010).

11.6.1.3 Accidental Exposure

Among the various agrochemicals, pesticides that are ingested by humans may cause serious illness, severe injury, or sometimes even death (Sarwar 2015). Generally, pesticides in sealed containers are less likely to create a more toxic condition. Dry pesticide sprayed into the soil can be dangerous to groundwater and other surrounding environments. Farmers are exposed to varieties of agrochemicals through dermal absorption through contaminated clothing or adhered dust and residues on floors and other surfaces (Macfarlane et al. 2013). Dermal exposure to pesticides is high in uncovered areas of the body like face, hands, and legs of the workers while applying the pesticides. This can be reduced by correct and protective application methods and also with the use of appropriate PPE (Damalas and Koutroubas 2016). In several occupations use of agricultural pesticides to domestic pest control has resulted in accidental poisoning (Balme et al. 2010). School-aged children and old aged population is more vulnerable to household pesticide exposure (Liu and Schelar 2012). In rural areas of South Africa, the ignorant use of pesticides to control bedbugs, fleas, and other pests in sleeping beds has resulted in the poisoning of children and household population (Bailie and Kelikian 1998).

In many instances, oral exposure to pesticides occurs through direct consumption of pesticides knowingly or unknowingly and by drinking water stored in used pesticide cans. Improper hand and body cleaning practices after pesticide application also contribute to the considerable quantum of oral exposure. On entering into the body, these notorious chemicals get absorbed along the gastrointestinal tract, enter the bloodstream, and get distributed throughout the body. Many cases of intentional suicide cases were of this kind and were found particularly high in developing countries (Damalas and Koutroubas 2016).

11.6.2 Health Risk of Agrochemicals

Several agrochemicals are capable of causing neurotoxicity and pathological symptoms. Environmental elements have also been identified as producing factors which trigger the common cellular process (Bastías-Candia et al. 2019). High prevalence of endemic nephropathy, a type of chronic kidney disease and the etiopathogenesis of chronic kidney diseases non-traditional (CKDnt) among agricultural communities are hypothesized that exposure to pesticides, heavy metals or metalloids, and other environmental contaminants are possible causes for the disease (Herrera Valdés et al. 2019). It has been stated that a relatively high level of population exposure to agrochemicals is alarming, which leads to chronic kidney disorders in the general population of El Salvador (Orantes-Navarro et al. 2019). Alteration in the vestibular system was verified in 50% of the workers, exposed to pesticide residues through various environmental sources (Zeigelboim et al. 2019). A questionnaire survey conducted by Marcelino et al. (2019) revealed that those farmers are exposed occupationally to pesticides due to the improper use of PPE products. Hence the study advocates that intensive assessments and awareness on safety practices and attitude change is required in harmful environmental and anthropogenic effects of pesticides. Table 11.1 summarizes the recent studies on agrochemical exposure and its associated health effects.

On reviewing all these studies, it was observed that exposure to agrochemicals through several sources and routes are highly significant and should be viewed with utmost importance to prevent or mitigate the adverse effect on humans.

11.7 Bio-Monitoring and Risk Assessment

Bio-monitoring refers to the use of living organisms or any kind of biotic factor in the environment to assess the presence of environmental contamination, like air or water or any specific region of interest. It can be done qualitatively by observing the physiological and behavioral changes in organisms, or quantitatively by measuring the magnitude of accumulation of chemicals in the tissues of the organism. It is an important and valuable tool for understanding the fate of agrochemicals in various compartments of the environment (Itzhaki et al. 2018). The data consolidated from bio-monitoring studies can be effectively used for framing health policies to the

Table 11.1 Exposure to agrochemicals and health effects among the exposed population

Exposure type	Population type	Health effects	References
Occupational exposure	Agricultural and sheep wool workers	About 30% of blood samples collected from agricultural and sheep wool workers showed exceeding levels of HCH above its prescribed tolerance limits	Dhananjayan et al. (2012a)
Occupational exposure	Agricultural workers	Reduced levels of AChE and BChE enzymes were recorded in blood samples of agricultural workers	Dhananjayan et al. (2012b)
Environmental exposure	Children	Allergies are more common in children exposed to pesticide environment	Hauptman and Phipatanakul (2015)
Agricultural chemicals	Agriculture workers	Herbicides are associated with premature mortality due to PD	Caballero et al. (2018)
Suicide	General population (youth)	Exposed population expressed psychological and clinical features like thoughts of self-harm, irritability and aggression, low self-esteem, non-adherence, family dispute, and financial distress	Abdullah et al. (2018)
Occupational exposure	Farmer	Lung cancer risk to the exposed cohort.	Boulanger et al. (2018)
Biopesticides	Human liver cells	Cytotoxic effect and oxidative DNA damage	Zhang et al. (2019)
Pesticides	Women	Hepatic toxicity in Colaisaca women (aspartate aminotransferase) and alanine aminotransferase) and an increased occurrence of micronuclei (MN), genetic polymorphisms in paraoxonase-1 and glutathione S-transferase protein 1 and effects on karyolitic cells, karyorrhectic cells, and condensed chromatin cells	Arévalo-Jaramillo et al. (2019)
Detergents and pesticides	Children	Association of prenatal exposure to pesticides to the impaired cognitive function in the children population of Lebanon	Hallit et al. (2019)
Fertilizers	Human	Fertilizers induce minimal uptake of heavy metals and the net loss of manganese from vegetables	Clarke-Lambert et al. (2019)
OP pesticides	Children	Evidence for an inverse relation of child nonverbal intelligence quotient (IQ) and late pregnancy urinary dialkyl phosphates (DAPs) due to agrochemical exposure	Jusko et al. (2019)
Chemical contamination in vegetables	Human	Risk assessment using hazardous quotient (HQ) and threshold of toxicological concern (TTC) approaches	Margenat et al. (2019)

(continued)

Table 11.1 (continued)

Exposure type	Population type	Health effects	References
		showed the risk of exposure to chemicals through consumption of vegetables with the high quantum of residues	
Occupational exposure	Women	A decrease in enzyme activities and DNA damage in tea garden women workers was due to mixed pesticides exposure	Dhananjayan et al. (2019)

related population subjected to its exposure, respectively. For instance, the bio-monitoring study exposed the occurrence of lead residues in US populations due to exposure to gasoline containing a high amount of lead. This, in turn, has forced the United States Environment Protection Agency (USEPA) to regulate the lead concentrations in gasoline. The post-bio-monitoring study after implementation of the regulations revealed the drop in lead concentration levels in the exposed population. Hence this clearly expresses the necessity of a bio-monitoring study to assess the impact of any agrochemical to humans or other non-targeted organisms (National Research Council—NRC 2006). Though there are several bio-monitoring studies conducted across the globe, they were not systematic and long term and were insufficient to provide a complete toxicity profile of the chemical under study. Besides the data generated also faces several challenges in terms of ethics and interpretation. Bio-monitoring has become an indispensable tool for studying occupational and environmental exposure to chemicals, including persistent organic pollutants (Sexton et al. 2004). Bio-monitoring data can be used to evaluate exposure assessments based on measurements in environmental media or on judgments regarding exposure potential. These data can also provide insight into the relative importance of various exposure pathways. Over time, such monitoring may also provide insight into the effectiveness of exposure interdiction strategies (Katsikantami et al. 2019). Due to the indiscriminate use of agrochemicals, it becomes significant to know the concept of bio-monitoring studies to understand its fate.

11.7.1 Principles and Methods of Bio-Monitoring

One of the most fundamental processes of living organisms, including human beings, animals, and plants, is their ability to respond to external stimuli, i.e. these stimuli activate processes which frequently help organisms to survive. In many cases, the pollutants in the environment, particularly agrochemical residues in air, water, soil, or any biological system can act as the stimuli inducing the unfavorable responses. The responses in any environment can also be shown by the entire community rather than a single species. The answer to the impact of any agrochemical can be monitored as a physical or, biological or behavioral or morphological change in the organisms or changes in the habitat characteristics. Sometimes the intra- and inter-specific relationship between the communities also serves as useful indicators in a bio-monitoring study. Most of the bio-monitoring studies are carried out in natural environments or habitats while a few reviews like toxicity tests and bioassays are also carried out in controlled environments or laboratories (Jackson et al. 2002).

The methods of bio-monitoring studies involve multiple stages involving several complicated processes. It includes a statement of the problem, delineation of hypothesis, selection of study, sampling methods, systematic investigation procedures, data collection and analyses, interpretation and communication. A simple assessment of physicochemical characterization of any agrochemical is not sufficient for any monitoring study, and it must be that a bio-monitoring study always includes the biological methods and environmental factors. The integration of all components of a review makes it a robust one which indicates the overall effects of the chemical contaminant to the environment and humans (United Nations Environment Program–World Health Organization UNEP/WHO 1996).

11.7.2 Selection of Appropriate Methods and Organisms

The choice of the appropriate method and a suitable indicator organism for a bio-monitoring study depend on several factors such as the aim of the study, interrelations between the various stages of the research, availability of resources, etc. However, a suitable method of bio-monitoring should be selected to provide appropriate and relevant information which are required and hence there lies the value of the bio-monitoring study (NRC 2006). The most important criteria involved in a bio-monitoring study are the selection of an indicator organism and the method of data collection and analysis. The most crucial factor is the selection of an appropriate means of a biological method which includes the exposure, type, duration, and responses. So, we have to understand and be well equipped to conduct and interpret bio-monitoring studies.

11.7.3 Risk Assessment and Management

The risk assessment and management methods involve hazard identification, hazard characterization and dose–response relationship assessment, exposure analysis, and characterization of risks. In general, risk assessment is an iterative process involving many steps like exposure assessment, reference dose calculation, hazard estimation, and risk characterization, etc. Under these stages, chemical concentrations at different matrices are associated with the human contact time, and dosage limits are calculated. Besides, many uncertainties like low-toxic profile, incomplete understanding of the mechanism of action, species variability, and insufficient exposure information make the process very complicated (NRC 2006). There is a general recognition that the assessment of chemicals on an individual basis does not reflect conditions in the environment or in humans, where a target site is typically exposed to various chemicals at the same time. This includes natural and anthropogenic compounds.

11.7.4 Ecotoxicological Databases

The outcome of the bio-monitoring studies and risk assessment studies are usually compiled by authenticated statutory agencies and will be released as a database. These databases will be released from time to time based on the periods of the conduct of the study and other dynamic variables relevant to the studies. Such reputed databases include Canada's Domestic Substance List, USEPA ECOTOX database, Organization for economic co-operation and development (OECD) Quantitative Structure-Activity Relationships Project [(Q)SARs], Registration, Evaluation, Authorization and Restriction of Chemicals (REACH - Council of the European Union. Regulation 2006); and the database of International Council of Chemical Associations 2018. These databases have generated a huge amount of reliable toxicity data which systematically identifies the hazard and its related risks to various non-targeted matrices. This has been widely used by researchers and policymakers to review the effects of the chemical contaminants. Worldwide, one million cases of involuntary poisonings and two million cases of voluntary ingestion of pesticides are reported every year (Recena et al. 2006). However, in developing countries and underdeveloped countries, such kind of databases is not available due to several reasons like improper use and management of chemicals, ignorance of the exposed population, and lack of adequate statutory guidelines.

Besides these generalized databases such as USEPA, Ecotoxicology Knowledge, European Chemical Agency Database, and Japan Ministry's Database are also available. All these datasets are more reliable in terms of specific classes of agrochemicals. The toxicological databases are the centralized repositories which make anybody to retrieve information to understand about the risks posed by a particular chemical, its adverse effects from the level of an individual organism to the entire community (Bejarano et al. 2016). For example, the USEPA's toxicity datasets meet out the requirements of user community by providing toxicity limits for a wide range of non-targeted biota from phytoplankton, fishes to large mammals including humans (Raimondo et al. 2016). These datasets also interrelate the toxicity levels between and among various species involved in the study for extrapolating toxicity between species and provides a comparative assessment (Busquet et al. 2014). It also addresses the lack of information and technical limitations of epidemiology and biostatistics of the study. But, specific databases for developing countries are still lacking.

11.8 Conclusions

In today's world, the use of agrochemicals had become inevitable to increase agricultural production across the globe to meet out the global food and fiber demands due to the exploding population levels. On the other hand, the negative harmful environmental effects caused due to the negligent use of agrochemicals should also be addressed on par, with much concern. Under this context, management tactics are required to emphasis on the minimal use of agrochemicals. Though the use of agrochemicals, mainly comprising pesticides and fertilizers, had resulted in the green revolution by increasing the agricultural yield and by the control of diseases, its adverse impact on the environment and the non-targeted organisms were alarming. Under this context, this chapter explains the source, usage pattern, and distribution of agrochemicals, mainly fertilizers and pesticides across several environmental components. Further, the bioaccumulation and biomagnifications pattern of these chemicals in the abiotic and biotic components of the environment prove their ecological persistence and fate. Besides, the exposure of the chemicals to the humans through environment, occupation, and accidents depicts the route of entry into the human systems. The appropriate information on its health risks will help the stakeholders to understand the effects of these chemicals. The importance of bio-monitoring studies and its related estimation of risks of any agrochemical and its residues are to be considered when providing the toxicity profile of the chemical and its management strategies. Controlled releases of agrochemical formulations have attracted considerable attention to reduce the rampant distribution of agrochemicals in the natural environment. It is the high time that actions have to be taken globally to protect the environment and to minimize the health hazards caused by the agrochemicals. The measures may include the methods of integrated pest management, using resistant varieties of seeds for cultivation and eco-friendly methods of pest control, and proper usage of agrochemicals. Awareness and induction activities to the farmers, along with extension activities, can be adapted to educate the agricultural community to adopt the strategies as mentioned earlier in methods. Hence the severe impact of agrochemicals, its usage, distribution, and fate in the environment should be clearly made known to the farmers and other related communities. The ways to minimize the impact and strategies to be followed to reduce the risks posed by the agrochemicals to the environment should be delineated, and the statutory bodies should provide regulated information to the common public. Proper, systematic, planned investigations, bio-monitoring and risk assessment studies, on the impact of the commonly used agrochemicals are highly warranted, to understand and mitigate their detrimental environmental effects.

11.9 Future Perspectives

Agrochemicals are being used extensively for several years. This has led to the contamination of soil, water, air, food, and other biotas of the global environment. Considering the impact of agrochemicals to the environment, it is necessary to devise viable alternatives for sustainable agricultural productivity and environmental protection. Outcomes through the use of natural biopesticides, biofertilizers, intensive farming techniques, and integrated pest management techniques were promising. Besides, the advent of technical methods for applying agrochemicals, genetic approaches in managing the pests have also reduced the dependency on agrochemicals to a greater extent. Still, these alternatives have to be given due importance by the developed countries, in particular, to replace the extensive use of agrochemicals through appropriate regulations and legislations. Development of new approaches for bio-monitoring of agrochemicals in the ecosystem could be devised to improve the bio-monitoring process limitations. Bio-monitoring studies integrated with big data generation through remote sensing techniques, geoinformatics, metagenomics, and next-generation sequencing techniques may revolutionize the ecological bio-monitoring of agrochemicals in the environment in the near future.

References

Abdullah M, Khalily MT, Ahmad I, Hallahan B (2018) Psychological autopsy review on mental health crises and suicide among youth in Pakistan. Asia Pac Psychiatry 10(4):e12338

Abhilash PC, Singh N (2009) Pesticide use and application: an Indian scenario. Health Phys 67 (3):280–282

Adhikari T, Biswas AK, Ajay Ramana S, Saha JK, Singh MV, Kundu S, Subba Rao A (2012) Heavy metal pollution in soil-plant system and its remediation. IISS Technical Bulletin, Indian Institute of Soil Science, Bhopal, pp 1–57

Adu P, Forkuo EK, Issah A, Asumadu IO, Cadman-Sackey E, Quarshie AAA, Gyabaa S, Ephraim RKD (2019) High incidence of moderately reduced renal function and lead bioaccumulation in agricultural workers in Assin south district, Ghana: a community-based case-control study. Int J Nephrol 2019:5368427

Aiassa DE, Manas FJ, Gentile NE, Bosch B, Salinero MC, Gorla NBM (2019) Evaluation of genetic damage in pesticides applicators from the province of Cordoba, Argentina. Environ Sci Pollut Res Int 26:20981–20988

Akoto O, Adiyiah J (2008) Dissolved nitrogen in drinking water resources of farming communities in Ghana. Afr J Environ Sci Technol 2(2):31–35

Alvarez A, Saez JM, Costa JSD (2017) Actinobacteria: current research and perspectives for bioremediation of pesticides and heavy metals. Chemosphere 166:41–62

Anjum MM, Ali N, Iqbal S (2017) Pesticides and environmental health: a review. Toxicol Environ Chem 5:555–671

Arévalo-Jaramillo P, Idrobo A, Salcedo L, Cabrera A, Vintimilla A, Carrión M, Bailon-Moscoso N (2019) Biochemical and genotoxic effects in women exposed to pesticides in Southern Ecuador. Environ Sci Pollut Res Int 14:325–331

Bailie DS, Kelikian AS (1998) Tarsal tunnel syndrome: diagnosis, surgical technique, and functional outcome. Foot Ankle Int 19:65–72

Baldi I, Robert C, Piantoni F, Tual S, Bouvier G, Lebailly P, Raherison C (2014) Agricultural exposure and asthma risk in the AGRICAN French cohort. Int J Hyg Environ Health 217 (4):435–442

Balme G, Hunter L, Goodman P, Ferguson H, Craigie J, Slotow R (2010) An adaptive management approach to trophy hunting of leopards (*Panthera pardus*): a case study from KwaZulu-Natal, South Africa. In: Macdonald DW, Loveridge A (eds) Biology and conservation of wild felids, 1st edn. Oxford University Press, Oxford, pp 341–351

Bastías-Candia S, Zolezzi JM, Inestrosa NC (2019) Revisiting the paraquat-induced sporadic Parkinson's disease-like model. Mol Neurobiol 56(2):1044–1055

Behfar A, Nazari Z, Rabiee MH, Raeesi G, Oveisi MR, Sadeghi N, Jannat B (2013) The organochlorine pesticides residue levels in Karun river water. Jundishapur J Nat Pharm Prod 8 (1):41–46

Bejarano AC, Farr JK, Jenne P, Chu V, Hielscher A (2016) The chemical aquatic fate and effects database (cafe), a tool that supports assessments of chemical spills in aquatic environments. Environ Toxicol Chem 35:1576–1586

Blacquiere T, Smagghe G, Cornelis AM, Gestel V, Mommaerts V (2012) Neonicotinoids in bees: a review on concentrations, side-effects and risk assessment. Ecotoxicology 212:973–999

BLI (2004) State of the world's birds. Birdlife International. http://www.biodiversityinfo.org/default.php

Bloomfeld SF, Stanwell-Smith R, Crevel RW, Pickup J (2006) Too clean, or not too clean: the hygiene hypothesis and home hygiene. Clin Exp Allergy 36(4):402–425

Boatman ND, Brickle NW, Hart JD, Milsom TP, Morris AJ, Murray AWA, Murray KA, Robertson PA (2004) Evidence for the indirect effects of pesticides on farmland birds. Ibis 146:131–143

Bonmatin JM, Giorio C, Girolami V, Goulson D, Kreutzweiser DP (2014) Environmental fate and exposure; neonicotinoids and fipronil. Environ Sci Pollut Res Int 22:35–67

Borgå K, Kidd KA, Muir DCG, Berglund O, Conder JM, Gobas FAPC, Kucklick J, Malm O, Powell DE (2011) Trophic magnification factors: considerations of ecology, ecosystems, and study design. Integr Environ Assess Manag 8(1):64–84

Boulanger M, Tual S, Lemarchand C, Guizard AV, Delafosse P, Marcotullio E, Pons R, Piel C, Pouchieu C, Baldi I, Clin B, Lebailly P (2018) Lung cancer risk and occupational exposures in crop farming: results from the agriculture and cancer (AGRICAN) cohort. Occup Environ Med 75(11):776–785

Brittain CA, Vighi M, Bommarco R, Settele J, Potts SG (2010) Impacts of a pesticide on pollinator species richness at different spatial scales. Basic Appl Ecol 11:106–115

Brühl CA, Schmidt T, Pieper S, Alscher A (2013) Terrestrial pesticide exposure of amphibians: an underestimated cause of global decline? Sci Rep 3:1135. https://doi.org/10.1038/srep01135

Busquet F, Strecker R, Rawlings JM et al (2014) OECD validation study to assess intra- and inter-laboratory reproducibility of the zebrafish embryo toxicity test for acute aquatic toxicity testing. Regul Toxicol Pharmacol 69:496–511

Caballero M, Amiri S, Denney JT, Monsivais P, Hystad P, Amram O (2018) Estimated residential exposure to agricultural chemicals and premature mortality by Parkinson's disease in Washington state. Int J Environ Res Public Health 15(12):28–85

Cai DW (2008) Understand the role of chemical pesticides and prevent misuses of pesticides. Bull Agric Sci Technol 1:36–38

Camargo ER, Senseman SA, Haney RL, Guice JB, McCauley GN (2013) Soil residue analysis and degradation of saflufenacil as affected by moisture content and soil characteristics. Pest Manag Sci 69:1291–1297

Capkin E, Altinok I, Karahan S (2006) Water quality and fish size affect toxicity of endosulfan, an organochlorine pesticide, to rainbow trout. Chemosphere 64:1793–1800

CDC (2016) Centre for disease control and prevention report, National Center for Health Statistics. Health, United States: With Chartbook on Long-term Trends in Health. Hyattsville, MD, pp 1–488

CEPA (1999) (Canadian Environmental Protection Act), Government of Canada. Canada Gazette Part III. 22. Canada, Ottawa, Ontario. Canada: Public Works and Government Services, 249 p

Christin MS, Menard L, Giroux I, Marcogliese DJ, Ruby S, Cyr D, Fournier M, Brousseau P (2013) Effects of agricultural pesticides on the health of Rana pipiens frogs sampled from the field. Environ Sci Pollut Res 20:601–611

Clarke-Lambert S, Hilaire DS, Stock J, Salako O, Lebetkin M, Nasimov U, Strothers J, Blasczak-Boxe A, Skeete D, Blaszczak-Boxe C (2019) The impact of fertilizers on the uptake of manganese in Cherry Belle radish plants: implications for human health. Environ Sci Pollut Res Int 26(10):10414–10428

Climent MJ, Herrero-Hernández E, Sánchez-Martín MJ, Rodríguez-Cruz MS, Pedreros P, Urrutia R (2019) Residues of pesticides and some metabolites in dissolved and particulate phase in surface stream water of Cachapoal River basin, Central Chile. Environ Pollut 251:90–101

Coronado GD, Holte S, Vigoren E, Griffith WC, Barr DB, Faustman E (2011) Organophosphate pesticide exposure and residential proximity to nearby fields: evidence for the drift pathway. Occup Environ Med 53:884–891

da Costa Chaulet F, de Alcantara Barcellos HH, Fior D, Pompermaier A, Koakoski G, da Rosa JGS, Fagundes M, Barcellos LJG (2019) Glyphosate- and fipronil-based agrochemicals and their mixtures change zebrafish behavior. Arch Environ Contam Toxicol 77:443–451

Damalas CA, Koutroubas SD (2016) Farmers' exposure to pesticides: toxicity types and ways of prevention. Toxics 4(1):1. https://doi.org/10.3390/toxics4010001

Das N, Mahanta C, Kumar M (2020) Water quality under the changing climatic condition: a review of the Indian scenario. In: Kumar M, Snow D, Honda R (eds) Emerging issues in the water environment during anthropocene. Springer Transactions in Civil and Environmental Engineering. Springer, Singapore

Dawson AH, Eddleston M, Senarathna L, Mohamed F, Gawarammana I, Bowe SJ, Manuweera G, Buckley NA (2010) Acute human lethal toxicity of agricultural pesticides: a prospective cohort study. PLoS Med 7:e1000357

Dereumeaux C, Fillol C, Quenel P, Denys S (2020) Pesticide exposures for residents living close to agricultural lands: a review. Environ Int 134:105–110

Dhananjayan V (2012a) Acetylcholinesterase and butyrylcholinesterase activity in brain and plasma of several species of birds from India. Res Rev J Toxicol 2(1):1–9

Dhananjayan V (2012b) Organochlorine pesticides and polychlorinated biphenyls in various tissues of waterbirds in Nalabana bird sanctuary, Chilika Lake, Orissa, India. Bull Environ Contam Toxicol 89(1):197–201

Dhananjayan V (2012c) Variation in persistent organochlorine pesticide residues among various tissues of house sparrow, Passer domesticus, from Tamil Nadu, India during 2001–2006. Res Rev J Ecol 1(2):16–24

Dhananjayan V (2013) Accumulation pattern of persistent organochlorine pesticides in liver tissues of various species of birds from India. Environ Sci Pollut Res 20(5):3149–3156

Dhananjayan V, Muralidharan S (2010a) Organochlorine pesticide residues in inland wetland fishes of Karnataka, India and their implications on human dietary intake. Bull Environ Contam Toxicol 85(6):619–623

Dhananjayan V, Muralidharan S (2010b) Levels of organochlorine pesticide residues in blood plasma of various species of birds from. India Bull Environ Contam Toxicol 85(2):129–136

Dhananjayan V, Muralidharan S (2013) Levels of polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and organochlorine pesticides in various tissues of white-backed vulture in India. Biomed Res Int 2013:190353

Dhananjayan V, Ravichandran B (2014) Organochlorine pesticide residues in foodstuffs, fish, wildlife, and human tissues from India: Historical Trend and Contamination Status. In: Malik A, Grohmann E, Akhtar R (eds) Environmental deterioration and human health. Springer, Dordrecht, pp 229–262

Dhananjayan V, Ravichandran B (2018) Occupataional health risk of farmers exposed to pesticides in agricultural activities. Curr Opin Environl Sci Heallth 4:31–37

Dhananjayan V, Muralidharan S, Jayanthi P (2011a) Distribution of persistent organochlorine chemical residues in blood plasma of three species of vultures from India. Environ Monit Assess 173(1–4):803–811

Dhananjayan V, Muralidharan S, Ranapratap S (2011b) Organochlorine pesticide residues in eggs and tissues of house sparrow, Passer domesticus, from Tamil Nadu, India. Bull Environ Contam Toxicol 87(6):684–688

Dhananjayan V, Ravichandran B, Rajmohan HR (2012a) Organochlorine pesticide residues in blood samples of agriculture and sheep wool workers in Bangalore (rural), India. Bull Environ Contam Toxicol 88(4):497–500

Dhananjayan V, Ravichandran B, Anitha N, Rajmohan HR (2012b) Assessment of acetylcholinesterase and butyrylcholinesterase activities in blood plasma of agriculture workers. Indian J Occup Environ Med 16(3):127–130

Dhananjayan V, Ravichandran B, Panjakumar K, Kalaiselvi K, Kausic R, Mala A, Avinash G, Shridhar K, Manju A, Rajesh W (2019) Assessment of genotoxicity and cholinesterase activity among women workers occupationally exposed to pesticides in tea garden. Mutat Res 841:1–7

Dhananjayan V, Jayakumar S, Ravichandran B (2020a) Conventional methods of pesticide application in agricultural field and fate of the pesticides in the environment and human health. In: Rakhimol KR et al (eds) Controlled release of pesticides for sustainable agriculture. https://doi.org/10.1007/978-3-030-23396-9_1

Dhananjayan V, Subramanian M, Rajamani J, Palaniyappan J, Samidurai J, Arumugam A (2020b) Levels and distribution pattern of organochlorine pesticide residues in eggs of 22 terrestrial birds from Tamil Nadu, India [published online ahead of print, 2020 Jul 8]. Environ Sci Pollut Res Int. https://doi.org/10.1007/s11356-020-09978-5

Erisman JW, Sutton MA, Galloway J, Klimont Z, Winiwarter W (2008) How a century of ammonia synthesis changed the world. Nat Geosci 1:636–639

FAO (Food and Agricultural Organization) (2019) World fertilizer trends and outlook to 2022. http://www.fao.org/3/ca6746en/CA6746EN.pdf

Favari L, Lopez E, Martinez-Tabche L, Dıaz-Pardo E (2002) Effect of insecticides on plankton and fish of Ignacio Ramirez reservoir (Mexico): a biochemical and biomagnification study. Ecotoxicol Environ Saf 51:177–186

FICCI (Federation of Indian Chambers of Commerce and Industry) (2016) Ushering in the 2nd green revolution: role of crop protection chemicals. Fine Chemicals Corporation. What are Agrochemicals? Jayhaws News. https://www.jayhawkchem.com/2018/05/11/what-are-agrochemicals/

FICCI (Federation of Indian Chambers of Commerce and Industry) (2019) Report on use of agrochemicals for sustainable farming. 8th Agrochemicals Conference 2019 - July 16, 2019, New Delhi, India. http://ficci.in/past-event-page.asp?evid=24230

Fishel FM (2013) Pesticides effects on non-target organisms. PI-85. Pesticide information office, Florida Cooperative Extension Service, IFAS, University of Florida, Gainesville, FL, USA; 2011. http://edis.ifas.ufl.edu/pi122. Accessed 14 Oct 2013

Floch C, Chevremont AC, Joanico K, Capowiez Y, Criquet S (2011) Indicators of pesticide contamination: soil enzyme compared to functional diversity of bacterial communities via Biolog® Ecoplates. Eur J Soil Biol 47:256–263

Garcia C, Hernandez T, Costa F (1997) Potential use of dehydrogenase activity as an index of microbial activity in degraded soils. Comm Soil Sci Plant Anal 28:123–134

Garron CA, Davis KC, Ernst WR (2009) Near-field air concentrations of pesticides in potato agriculture in Prince Edward Island. Pest Manag Sci 65:688–696

Gill RJ, Ramos-Rodriguez O, Raine NE (2012) Combined pesticide exposure severely affects individual- and colony-level traits in bees. Nature 491:105–108

Gobas FAPC, de Wolf W, Verbruggen E, Plotzke K, Burkhard L (2009) Revisiting bioaccumulation criteria for POPs and PBT assessments. Integr Environ Assess Manag 5 (4):624–637

Godfray HC, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327(5967):812–818

Grandjean P, Landrigan PJ (2006) Developmental neurotoxicity of industrial chemicals. Lancet 368:2167–2178. https://doi.org/10.1016/S0140-6736(06)69665-7

Gupta PK (2019) Concept and applications of veterinary toxicology: an interactive guide. Springer, Cham. https://doi.org/10.1007/978-3-030-22250-5

Hallit S, Haddad C, Zeidan RK, Obeid S, Kheir N, Khatchadourian T, Salameh P (2019) Cognitive function among schoolchildren in Lebanon: association with maternal alcohol drinking and smoking during pregnancy and domestic use of detergents and pesticides during childhood. Environ Sci Pollut Res Int 26(14):14373–14381

Handa SK, Agnihotri NP, Kulshreshtha G (1999) Effect of pesticide on soil fertility. In: Pesticide residues; significance, management and analysis. Research Publication & Book Publication House, Houston, pp 184–198

Hargrave BT, Harding GC, Vass WP, Erickson PE, Fowler BR, Scott V (1992) Organochlorine pesticides and polychlorinated biphenyls in the Arctic Ocean food web. Archi Environ Contamin Toxicol 22:41–54

Hauptman M, Phipatanakul W (2015) Year in review: Pediatric allergy and asthma, excluding food allergy. Ann Allergy Asthma Immunol 114(3):175

Henry M, Bèguin M, Requier F, Rollin O, Odoux J-F, Aupinel P, Aptel J, Tchamitchian S, Decourtye A (2012) A common pesticide decreases foraging success and survival in honey bees. Science 336:348–350

Herrera Valdés R, Almaguer López M et al (2019) Chronic interstitial nephritis of nontraditional causes in Salvadoran agricultural communities. Clin Nephrol 92:1–8

Hill GK, Garg H (2014) Pesticides: Environmental impacts and management strategies, pesticides - Toxic aspects, Marcelo L. Larramendy and Sonia Soloneski, IntechOpen, pp 1–40. https://doi.org/10.5772/57399

Horn S, Pieters R, Bøhn T (2019) May agricultural water sources containing mixtures of agrochemicals cause hormonal disturbances? Sci Total Environ 23:134862. https://doi.org/10.1016/j.scitotenv.2019.134862

Huang H, Ding Y, Chen W, Zhang Y, Chen W, Chen Y, Mao Y, Qi S (2019) Two-way long-range atmospheric transport of organochlorine pesticides (OCPs) between the Yellow River source and the Sichuan Basin, Western China. Sci Total Environ 651:3230–3240

Hung DQ, Thiemann W (2002) Contamination by selected chlorinated pesticides in surface waters in Hanoi, Vietnam. Chemosphere 47(4):357–367

Hussain S, Siddique T, Saleem M, Arshad M, Khalid A (2009) Impact of pesticides on soil microbial diversity, enzymes, and biochemical reactions. Adv Agron 102:159–200

Ibrahim L, Preuss TG, Ratte HT, Hommen U (2013) A list of fish species that are potentially exposed to pesticides in edge-of-field water bodies in the European Union-a first step towards identifying vulnerable representatives for risk assessment. Environ Sci Pollut Res 20:2679–2687

IFA (International Fertilizer Association) (2019) Fertilizer outlook 2019–2023. Annual Conference, Montreal, 11–13 June 2019, PIT, Market Intelligence and Agriculture Services. http://2019_ifa_annual_conference_montreal_public_summary.pdf

Isin S, Yildirim I (2007) Fruit-growers' perceptions on the harmful effects of pesticides and their reflection on practices: the case of Kemalpasa, Turkey. Crop Prot 26:917–922

Ismael LL, Rocha EMR (2019) Estimate of the contamination of groundwater and surface water due to agrochemicals in the sugar-alcohol area, Santa Rita, State of Paraíba, Brazil. Cien Saude Colet 24(12):4665–4676

Itzhaki ZB, López ME, Puttaswamy N, Tamar BT (2018) A review of human biomonitoring in selected Southeast Asian countries. Environ Int 116:156–164

Jackson RB, Banner JL, Jobbagy EG, Pockman WT, Wall DH (2002) Ecosystem carbon loss with woody plant invasion of grasslands. Nature 418:623–626

Jangir CK, Singh D, Kumar S (2016) Yield and economic response of biofertilizer and fertility levels on black gram (*Vigna mungo* L.). Prog Res An Int J 11(Special-VIII):5252–5254

Jangir CK, Kumar S, Lakhran H, Meena RS (2017) Towards mitigating malnutrition in pulses through biofortification. Trends Bios 10(17):2999–3002

Jayakumar S, Muralidharan S, Dhananjayan V (2019) Levels of organochlorine pesticide residues in fresh water fishes of three bird sanctuaries in Tamil Nadu, India. Environ Sci Pollut Res Int 26 (2):1983–1993

Jayakumar S, Muralidharan S, Dhananjayan V (2020) Organochlorine pesticide residues among colonial nesting birds in Tamil Nadu, India: a Maiden assessment from their breeding grounds. Arch Environ Contam Toxicol 78(4):555–567

Johnson LA, Welch B, Whitfield SM (2013) Interactive effects of pesticide mixtures, predators, and environmental regimes on the toxicity of two pesticides to red-eyed tree frog larvae. Environ Toxicol 32:2379–2386

Jusko TA, van den Dries MA, Pronk A, Shaw PA, Guxens M, Spaan S, Jaddoe VW, Tiemeier H, Longnecker MP (2019) Organophosphate pesticide metabolite concentrations in urine during pregnancy and offspring nonverbal IQ at age 6 years. Environ Health Perspect 127(1):17007. https://doi.org/10.1289/EHP3024

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in Indo-Gangatic Plains of India. Int J Curr Microb Appl Sci 6(3):152–163

Katsikantami I, Colosio C, Alegakis A, Tzatzarakis M, Vakonaki E, Rizos A, Sarigiannis D, Tsatsakis A (2019) Estimation of daily intake and risk assessment of organophosphorus pesticides based on biomonitoring data - the internal exposure approach. Food Chem Toxicol 123:57–71

Kerby JL, Richards-Hrdlicka KL, Storfer A, Skelly DK (2010) An examination of amphibian sensitivity to environmental contaminants: are amphibians poor canaries? Ecol Lett 13:60–67

Kevan PG (1999) Pollinators as bio-indicators of the state of the environments: species, activity and diversity. Agric Ecosyst Environ 74:373–393

Khailani MH, Tawfiq M, Al-Antary TMA, Alawi MA (2019) Monitoring of pesticides residues in soil samples from the southern districts of Jordan in 2016/2017. Toxin Rev 5:1–8

Khairy P, Shohoudi A, Mercier LA, Dore A, Marcotte F, Miró J, Avila-Alonso P, Ibrahim R, Asgar A, Poirier N, Mongeon FP (2017) Shone complex: an under-recognized congenital heart disease with substantial morbidity in adulthood. Can J Cardiol 33(2):253–259

Khan N, Kennedy A, Cotton J, Brumby S (2019) A pest to mental health? Exploring the link between exposure to agrichemicals in farmers and mental health. Int J Environ Res Public Health 16(8):1327. https://doi.org/10.3390/ijerph16081327

Khan MI, Shoukat MA, Cheema SA, Arif HN, Niazi NK, Azam M, Bashir S, Imran Ashraf I, Qadri R (2020) Contamination and exposure of pesticides in Pakistan: a review. Pak J Agric Sci 57 (1):131–149

Kittusamy G, Kandaswamy C, Kandan N, Subramanian M (2014) Pesticide residues in two frog species in a paddy agroecosystem in Palakkad District, Kerala, India. Bull Environ Contamin Toxicol 93(6):728–734

Korkmaz K (2007) Tarım Girdi Sisteminde Azot ve Azot Kirliliği. Available: http://www.ziraat.ktu.edu.tr/tarim_girdi.html

Kubiak R, Burkle L, Cousins I, Hourdakis A, Jarvis T, Jene B (2008) Pesticides in air: considerations for exposure assessment. Report of the FOCUS Working Group on Pesticides in Air, EC Document Reference SANCO/10553/2006, Rev 2 June, 327–328

Kudagammana ST, Mohotti K (2018) Environmental exposure to agrochemicals and allergic diseases in preschool children in high grown tea plantations of Sri Lanka. Allergy Asthma Clin Immunol 14:84. https://doi.org/10.1186/s13223-018-0308-z

Kumar R, Kranthi S, Nitharwal M, Jat SL, Monga D (2012) Influence of pesticides and application methods on pest and predatory arthropods associated with cotton. Phytoparasitica 40:417–424

Kumar S, Karaliya SK, Chaudhary S (2017a) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. Int J Curr Microb Appl Sci 6 (3):142–151

Kumar S, Meena RS, Pandey A, Seema (2017b) Soil acidity management and an economics response of lime and sulfur on sesame in an alley cropping system. Int J Curr Microb Appl Sci 6(3):2566–2573

Kumar S, Meena RS, Yadav GS, Pandey A (2017c) Response of sesame (*Sesamum indicum* L.) to Sulphur and lime application under soil acidity. Int J Plant Soil Sci 14(4):1–9

Kumari M (2012) Effects of organophosphate pesticide abate on the ovary of the cat fish, *Heteropneustes fossilis* (Bloch.). Bangladesh J Zool 40:207–212

Larson SJ, Capel PD, Majewski M (2010) Pesticides in surface waters: distribution, trends, and governing factors (No. 3). CRC Press, Chelsea

Lebedev AT, Mazur DM, Polyakova OV (2018) Semi volatile organic compounds in the snow of Russian Arctic islands: archipelago Novaya Zemlya. Environ Pollut 239:416–427

Lee JY, Kang HS, Noh SD, Woo JH, Lee PL (2011) NESIS: a neutral schema for a web-based simulation model exchange service across heterogeneous simulation software. Int J Comput Integr Manuf 24:948–969

Leite SB, Franco de Diana DM, Segovia Abreu JA, Avalos DS, Denis MA, Ovelar CC, Samaniego Royg MJ, Thielmann Arbo BA, Corvalan R (2019) DNA damage induced by exposure to pesticides in children of rural areas in Paraguay. Indian J Med Res 150(3):290–296

Lenka S, Rajendiran M, Vassanda Coumar ML, Dotaniya SJK (2016) Impact of fertilizers use on environmental quality souvenir of national seminar on “Environmental concern for fertilizer use in future” at Bidhan Chandra Krishi Viswavidyalaya, Kalyani on February 26

Liu J, Schelar E (2012) Pesticide exposure and child neurodevelopment: summary and implications. Work Place Health Saf 60(5):235–243

Lu C, Tian H (2017) Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. Earth Syst Sci Data 9:181–192. https://doi.org/10.5194/essd-9-181-2017

Luo ZL, Zhang Y, Mou S, Cui Z, Gu J, Yu MX (2019) Multi-residue analysis of plant growth regulators and pesticides in traditional Chinese medicines by high-performance liquid chromatography coupled with tandem mass spectrometry. Anal Bioanal Chem 411:2447–2460

Macfarlane E, Carey R, Keegel T, El-Zaemay S, Fritschi L (2013) Dermal exposure associated with occupational end use of pesticides and the role of protective measures. Saf Health Work 4 (3):136–141. https://doi.org/10.1016/j.shaw.2013.07.004

Mancini M, Bloem BR, Horak FB, Lewis SJG, Nieuwboer A, Nonnekes J (2019) Clinical and methodological challenges for assessing freezing of gait: future perspectives. Mov Disord 34 (6):783–790

Marcelino AF, Wachtel CC, Ghisi NC (2019) Are our farm workers in danger? Genetic damage in farmers exposed to pesticides. Int J Environ Res Public Health 16(3):358. https://doi.org/10.3390/ijerph16030358

Margenat A, Matamoros V, Díez S, Cañameras N, Comas J, Bayona JM (2019) Occurrence and human health implications of chemical contaminants in vegetables grown in peri-urban agriculture. Environ Int 124:49–57

Masoner JR, Kolpin DW, Cozzarelli IM et al (2019) Urban Stormwater: an overlooked pathway of extensive mixed contaminants to surface and ground waters in the United States. Environ Sci Technol 53(17):10070–10081

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena RS, Gogoi N, Kumar S (2017) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Megharaj M, Boul HL, Thiele JH (1999) Effects of DDT and its metabolites on soil algae and enzymatic activity. Biol Fert Soils 29:130–134

Mew EJ, Padmanathan P, Konradsen F, Eddleston M, Chang SS, Phillips MR, Gunnell D (2017) The global burden of fatal self-poisoning with pesticides 2006-15: systematic review. J Affect Disord 219:93–104

Mineau P, Whiteside M (2013) Pesticide acute toxicity is a better correlate of US grassland bird declines than agricultural intensification. PLoS One 8:e57457

Mitra A, Chatterjee C, Mandal FB (2011) Synthetic chemical pesticides and their effects on birds. Res J Environ Toxicol 5:81–96

Mordor Report (2019) https://www.mordorintelligence.com/industry-reports/agrochemicals-market

Mostafalou S, Abdollahi M (2012) Concerns of environmental persistence of pesticides and human chronic diseases. Clin Exper Pharmacol 2(1):1–3

Munoz-Leoz B, Ruiz-Romera E, Antiguedad I, Tebuconazole GC (2011) Application decreases soil microbial biomass and activity. Soil Biol Biochem 43:2176–2183

Murage EW, Voroney PR, Kay BD, Deen B, Beyaert RP (2007) Dynamics and turnover of soil organic matter as affected by tillage. Soil Sci Soc Am J 71:1363–1370

Muralidharan S, Dhananjayan V, Risebrough R, Prakash V, Jayakumar R, Bloom PH (2008) Persistent organochlorine pesticide residues in tissues and eggs of white-backed vulture, Gyps bengalensis from different locations in India. Bull Environ Contamin Toxicol 81(6):561–565

Muralidharan S, Dhananjayan V, Jayanthi P (2009) Organochlorine pesticides in commercial marine fishes of Coimbatore, India and their suitability for human consumption. Environ Res 109(1):15–21

Muralidharan S, Jayakumar S, Dhananjayan V (2012) Status of pesticide contamination in birds in India with special reference to threatened species. In: Rahmani AR (ed) Threatened birds in India: their conservation and requirement. Oxford University Press, BNHS, Mumbai, pp 73–91

Muralidharan S, Ganesan K, Nambirajan K, Kirubanandhini V, Dhananjayan V (2015) Wetland birds-indicators of pesticide contamination current and future prospects for research in India. In: ENVIS Bulletin Water birds of India, WII, Dehradun, India. Issue 16, Chapter 22, pp 314–323

Murray DL, Taylor PL (2000) Claim no easy victories: evaluating the pesticide industry's Global Safe Use campaign. World Develop 28:1735–1749

NPIC (National Pesticide Information Center) (2016) Pesticides and water resources. http://npic.orst.edu/envir/waterenv.html

NRC- National Research Council (2006) Human biomonitoring for environmental chemicals. The National Academies Press, Washington, DC. https://doi.org/10.17226/11700

Orantes-Navarro CM, Almaguer-López MM, Alonso-Galbán P, Díaz-Amaya M, Hernández S, Herrera-Valdés R, Silva-Aycaguer LC (2019) The chronic kidney disease epidemic in El Salvador: a cross-sectional study. Med Rev 21:29–37

Pal R, Tah J (2012) Biodegradation and bioremediation of pesticides in soil: its objectives, classification of pesticides, factors and recent developments. World J Sci Technol 2:36–41

Pan-Germany (2012) Pesticide and health hazards. Facts and figures 1–16. www.pan-germany.org/download/Vergift_EN-201112-web.pdf

Paoletti MG (1999) Using bioindicators based on biodiversity to assess landscape sustainability. Agric Ecosyst Environ 74:1–18

Pelosi C, Barot S, Capowiez Y, Hedde M, Vandenbulcke F (2013) Pesticides and earthworms. Agron Sustain Develop:1–30. https://doi.org/10.1007/s13593-013-0151-z

Pereira L, Fernandes MN, Martinez CB (2013) Hematological and biochemical alterations in the fish Prochilodus lineatus caused by the herbicide clomazone. Environ Toxicol Pharmacol 36:1–8

Pettis JS, van Engelsdorp D, Johnson J, Dively G (2012) Pesticide exposure in honey bees results in increased levels of the gut pathogen Nosema. Nat Wissenschaften 99:153–158

Pimentel D (1997) Techniques for reducing pesticide use: Environmental and economic benefits. John Wiley and Sons, Chichester, USA National Water Quality Assessment Program: Water-Resources Investigations Report. Report nr 99-4007

Qu C, Albanese S, Lima A, Hope D, Pond P, Fortelli A, Romano N, Cerino P, Pizzolante A, Vivo B (2019) The occurrence of OCPs, PCBs, and PAHs in the soil, air, and bulk deposition of the Naples metropolitan area, southern Italy: implications for sources and environmental processes. Environ Int 124:89–97

Quaghebeur W, Mulhern RE, Ronsse S, Heylen S, Blommaert H, Potemans S, Valdivia Mendizábal C, Terrazas García J (2019) Arsenic contamination in rainwater harvesting tanks around Lake Poopó in Oruro, Bolivia: an unrecognized health risk. Sci Total Environ 688:224–230

Raherison C, Baldi I, Pouquet M, Berteaud E, Moesch C, Bouvier G, Canal-Raffin M (2018) Pesticides exposure by air in vineyard rural area and respiratory health in children: a pilot study. Environ Res 169:189–195

Raimondo S, Lilavois CR, Barron MG (2016) Web-based interspecies correlation estimation (Web-ICE) for acute toxicity: User Manual. Ver 3.3. EPA/600/R-15/192. Office of Research and Development, US Environmental Protection Agency, Gulf Breeze, FL

Ravier I, Haouisee E, Clément M, Seux R, Briand O (2005) Field experiments for the evaluation of pesticide spray-drift on arable crops. Pest Manag Sci 61:728–736

Ravier S, Desert M, Gille G, Armegaud A, Wortham H, Quivet E (2019) Monitoring of glyphosate, glufosinate-ammonium, and (Aminomethyl) phosphonic acid in ambient air of Provence-Alpes-Côte-d'Azur Region. France Atmosphe Environ 204(1):102–109

REACH - Council of the European Union. Regulation (2006) (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency

Recena MC, Caldas ED, Pires DX, Pontes ER (2006) Pesticides exposure in Culturama, Brazil-knowledge, attitudes, and practices. Environ Res 102:230–236

Reinecke SA, Reinecke AJ (2007) The impact of organophosphate pesticides in orchards on earthworms in the Western Cape, South Africa. Ecotoxicol Environ Saf 66:244–251

Relyea RA (2005) The impact of insecticides and herbicides on the biodiversity and productivity of aquatic communities. Ecol Appl 15:618–627

Relyea RA (2012) New effects of roundup on amphibians: predators reduce herbicide mortality; herbicides induce antipredator morphology. Ecol Appl 22:634–647

Relyea RA, Hoverman JT (2008) Interactive effects of predators and a pesticide on aquatic communities. Oikos 117:1647–1658

Requena M, Tesifón P, Angela N, Jessica G, María IV, Antonio FH, Raquel A (2018) Association between environmental exposure to pesticides and epilepsy. Neurotoxicology 68:13–18

Requena M, López-Villén A, Hernández AF, Tesifón P, Ángela N, Raquel A (2019) Environmental exposure to pesticides and risk of thyroid diseases. Toxicol Lett 315:55–63

Richter ED (2002) Acute human pesticide poisonings. In: Pimentel D (ed) Encyclopedia pest management. Dekker, New York, pp 3–6

Rodríguez AGP, León JAA (2020) Methods for determination of pesticides and fate of pesticides in the fields. In: Rakhimol KR, Thomas S, Volova T, Jayachandran K (eds) Controlled release of pesticides for sustainable agriculture. Springer, Cham

Romero E, Fernández-Bayo J, Díaz JMC, Nogale R (2010) Enzyme activities and diuron persistence in soil amended with vermicompost derived from spent grape marc and treated with urea. Appl Soil Ecol 44:198–204

Ronquillo MG, Hernandez JCA (2017) Antibiotic and synthetic growth promoters in animal diets: review of impact and analytical methods. Food Control 72:255–267

Samaranda C, Gavrilescu M (2008) Migration and fate of persistent organic pollutants in the atmosphere - a modelling approach. Environ Eng Manag J 7:743–761

Santovito A, Cervella P, Delpero M (2012) Chromosomal aberrations in cultured human lymphocytes treated with the fungicide, Thiram. Drug Chem Toxicol 5:347–351

Saruchi Kumar V, Mittal H, Alhassan SM (2019) Biodegradable hydrogels of tragacanth gum polysaccharide to improve water retention capacity of soil and environment-friendly controlled release of agrochemicals. Int J Biol Macromol 132:1252–1261

Sarwar M (2015) The dangers of pesticides associated with public health and preventing of the risks. Int J Bioinform Biomed Eng 1:130–136

Satyavani G, Gopi RA, Ayyappan S, Balakrishnamurthy P, Reddy PN (2011) Toxicity effect of expired pesticides to freshwater fish, Labeo rohita. J Agric Environ 12:1–9

Scholz NL, Fleishman E, Brown L, Werner I, Johnson ML, Brooks ML, Michaelmore CL, Schlenk D (2012) A perspective on modern pesticides, pelagic fish declines, and unknown ecological resilience in highly managed ecosystems. Bio Sci 62:428–434

Schreck E, Geret F, Gontier L, Treihou M (2008) Neurotoxic effect and metabolic responses induced by a mixture of six pesticides on the earthworm Aporrectodea caliginosa noctuma. Chemosphere 71:1832–1839

Sebiomo A, Ogundero VW, Bankole SA (2011) Effect of four herbicides on microbial population, soil organic matter and dehydrogenase activity. Afr J Biotechnol 10:770–778

Sexton K, Needham LL, Pirkle JL (2004) Human biomonitoring of environmental chemicals: measuring chemicals in human tissue is the “gold standard” for assessing the people’s exposure to pollution. Am Sci 92(1):39–45

Sharma A, Kumar V, Shahzad B, Tanveer M, Sidhu GPS, Handa N, Kohli SK, Yadav P, Bali AS, Parihar RD, Dar OI, Singh K, Jasrotia S, Bakshi P, Ramakrishnan M, Kumar S, Bhardwaj R, Thukral AK (2019a) Worldwide pesticide usage and its impacts on ecosystem. SN Appl Sci 1:14–46

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019b) Growth, yield and quality of cluster bean (*Cyamopsis tetragonoloba*) as influenced by integrated nutrient management under alley cropping system. Indian J Agri Sci 89(11):1876–1880

Sidhu GK, Singh S, Kumar V, Dhanjal DS, Datta S, Singh J (2019) Toxicity, monitoring and biodegradation of organophosphate pesticides: a review. Critical Rev Environ Sci Technol 49 (13):1135–1187

Silva V, Mol HGJ, Zomer P, Tienstra M, Ritsema CJ, Geissen V (2019) Pesticide residues in European agricultural soils – a hidden reality unfolded. Sci Total Environ 653:1532–1545

Singh B, Mandal K (2013) Environmental impact of pesticides belonging to newer chemistry. In: Dhawan AK, Singh B, Brar-Bhullar M, Arora R (eds) Integrated pest management. Scientific Publishers, Jodhpur, pp 152–190

Singh VK, Singh M, Singh SK, Kumar C, Kumar A (2019) Sustainable agricultural practices using beneficial fungi under changing climate scenario. In: Choudhary KK, Kumar A, Singh AK (eds) Climate change and agricultural ecosystems -current challenges and adaptation. Wood Head Publishing, Cambridge, pp 25–42

Sjerps R, Kooij PJF, van Loon A, Van Wezel AP (2019) Occurrence of pesticides in Dutch drinking water sources. Chemosphere 235:510–518

Smith PN, Afzal M, Al-Hasan R, Bouwman K, Castillo LE, Depledge MH, Muralidharan S, Dhananjayan V et al (2010) Global perspectives on wildlife toxicology: emerging issues. In: Kendall RJ, Lacher TE, Cobb GP, Cox SB (eds) Wildlife toxicology: emerging contaminant and biodiversity issues. Taylor and Francis Group, CRC Press, Boca Raton, FL, pp 197–255

Soares WL, Porto MFD (2009) Estimating the social cost of pesticide use: an assessment from acute poisoning in Brazil. Ecol Econ 68:2721–2728

Socorro J, Durand A, Temime-Roussel B, Gligorovski S, Wortham H, Quivet E (2016) The persistence of pesticides in atmospheric particulate phase: an emerging air quality issue. Sci Rep 6(1):33456. https://doi.org/10.1038/srep33456

Sofo A, Scopa A, Dumontet S, Mazzatura A, Pasquale V (2012) Toxic effects of four sulphonylureas herbicides on soil microbial biomass. J Environ Sci Health Part B 47:653–659

Solaimalai A, Ramesh RT, Baskar M (2004) Pesticides and environment. In: Environ Contam Bioreclam, pp 345–382

Sonmez M, Kaplan S, Sonmez (2008) Environmental of chemical fertilizers effects on water pollution and solution proposals. West Medit Agri l Res Inst Derim J 25(2):24–34

Srinivasulu M, Mohiddin GJ, Madakka M, Rangaswamy V (2012) Effect of pesticides on the population of Azospirillum sp. and on ammonification rate in two soils planted to groundnut (*Arachis hypogaea* L.). Tropi Ecol 53:93–104

Stuart SN, Chanson JS, Cox NA, Young BE, Rodrigues ASL, Fischman DL, Waller RW (2004) Status and trends of amphibian declines and extinctions worldwide. Science 306:1783–1786

Taiwo AM (2019) A review of environmental and health effects of organochlorine pesticide residues in Africa. Chemosphere 220:1126–1140

Tang FL, Zhang M, Xu JF et al (2014) Pollution characteristics and health risk assessment of organochlorine pesticides (OCPs) in the Water of Lake Qiandao and Its Major Input Rivers. Huan Jing Ke Xue 35(5):1735–1741

Tekwa IJ, Ambali OY, Gabdo BH (2010) Economic analysis of farm hazards associated with the use of agrochemicals on agricultural farms. Aust J Agric Eng 1(1):7–13

Thiour-Mauprivez C, Martin-Laurent F, Calvayrac C, Barthelmebs L (2019) Effects of herbicide on non-target microorganisms: towards a new class of biomarkers? Sci Total Environ 684:314–325

Thiruchelvam M, Brockel BJ, Richfield EK, Baggs RB, CorySlechta DA (2000) Potentiated and preferential effects of combined paraquat and maneb on nigrostriatal dopamine systems: environmental risk factors for Parkinson's disease? Brain Res 873:225–234

Tien CJ, Chen CS (2012) Assessing the toxicity of organophosphorous pesticides to indigenous algae with implication for their ecotoxicological impact to aquatic ecosystems. J Environ Sci Heal Part B 47:901–912

Tierney KB, Baldwin DH, Hara TJ, Ross PS, Scholz NL, Kennedy CJ (2010) Olfactory toxicity in fishes. Aqua Toxicol 96:2–26

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418:671–677

Tsai MS, Chen MH, Lin CC, Liu CY, Chen PC (2019) Children's environmental health based on birth cohort studies of Asia (2) –air pollution, pesticides, and heavy metals. Environ Res 179 (Pt A):108754. https://doi.org/10.1016/j.envres.2019.108754

Tunstall Pedoe H, Woodward M, Tavendale R (2004) Pesticide pollution remains severe after cleanup of a stockpile of obsolete pesticides at Vikuge, Tanzania. Ambio A J Hum Environ 33:503–508

Udeigwe TK, Teboh JM, Eze PN (2015) Implications of leading crop production practices on environmental quality and human health. J Environ Manag 151:267–279

UNEP/WHO (1996) Water quality monitoring—a practical guide to the design and implementation of freshwater quality studies and monitoring programmes Edited by Jamie Bartram and Richard Ballance Published on behalf of United Nations Environment Programme and the World Health Organization

Unsworth J (2010) The history of pesticides, organic pesticides, September 19th 2008. http://blog.ecosmart.com/index.php/2008/09/19/the-history-of-pesticides/

US Environmental Protection Agency [USEPA] (1976) Toxic substances control act (1976). USEPA, Washington DC

USEPA (2009) The value of country working together to regulate pesticides and food safety—chieving public health and environmental protection through international collaboration. http://www.epa.gov/oppfead1/international/2009/workingtogether.pdf

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan region, India. Int J Chem Stud 5(4):1558–1560

Vickerman GP (1988) Farm scale evaluation of the long-term effects of different pesticide regimes on the arthropod fauna of winter wheat. In: Greeves MP, Grieg-Smith PW, Smith BD (eds) Field methods for the environmental study of the effects of pesticides. BCPC Monograph No. 40. British Crop Protection Council, Farnham, pp 127–135

Wang S, Steiniche T, Romanak KA, Johnson E, Quirós R, Mutegeki R, Wasserman MD, Venier M (2019) Atmospheric occurrence of legacy pesticides, current use pesticides, and flame retardants in and around protected areas in Costa Rica and Uganda. Environ Sci Technol 53 (11):6171–6181

Ware GW (1980) Effects of pesticides on non-target organisms. Residue Rev 76:173–201

Whitehorn PR, O'Connor S, Wackers FL, Goulson D (2012) Neonicotinoid pesticide reduces bumble bee colony growth and queen production. Science 336:351–352

Williams T (1997) Silent scourge. Audubon 99:28–35

Wilson NK, Strauss WJ, Iroz-Elardo N, Chuang JC (2010) Exposures of preschool children to chlorpyrifos, diazinon, pentachlorophenol, and 2,4-dichlorophenoxyacetic acid over 3 years from 2003 to 2005: a longitudinal model. J Expos Sci Environ Epidemiol 20:546–558

Woodrow JE, Gibson KA, Seiber JN (2018) Pesticides and related toxicants in the atmosphere. Rev Environ Contam Toxicol 247:147–196. https://doi.org/10.1007/398_2018_19

Wu JY, Smart MD, Anelli CM, Sheppard WS (2012) Honey bees (*Apis mellifera*) reared in brood combs containing high levels of pesticide residues exhibit increased susceptibility to Nosema (Microsporidia). J Invertebr Pathol 109:326–329

Xie H, Gao F, Tan W, Wang SG (2011) A short-term study on the interaction of bacteria, fungi and endosulfan in soil microcosm. Sci Tot Environ 412:375–379

Yang R, Lu A, Shi J, Jiang G (2005) The levels and distribution of organochlorine pesticides (OCPs) in sediments from the Haihe River, China. Chemosphere 61:347–354

Yasmin S, D'Souza D (2010) Effects of pesticides on the growth and development of earthworm: a review. Appl Environ Soil Sci 2010:678360

Yu H, Liu Y, Shu X, Ma L, Pan Y (2020) Assessment of the spatial distribution of organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) in urban soil of China, Chemosphere 243: 125 A. B. M. 129

Zeigelboim BS, Malisky JS, Rosa MRD, Lacerda ABM, Alcaraz PS, Fonseca VR (2019) The importance of otoneurological evaluation in Brazilian workers exposed to pesticides: a preliminary study. Int Arch Otorhinolaryngol 23:389–395

Zhang WJ (2018) Global pesticide use: profile, trend, cost/benefit and more. Proc Int Acad Ecol Environ Sci 8(1):1–27

Zhang M, Liang Y, Zhang X, Xu Y, Dai H, Xiao W (2008) Deletion of yeast CWP genes enhances cell permeability to genotoxic agents. Toxicol Sci 103:68–76

Zhang WJ, Jiang FB, Ou JF (2011) Global pesticide consumption and pollution: with China as a focus. Proc Int Acad Ecol Environ Sci 1(2):125–144

Zhang L, Yan C, Guo Q, Zhang J, Menzivar JR (2018) The impact of agricultural chemical inputs on environment: global evidence from informetrics analysis and visualization. Int J Low Carbon Technol 13(4):338–352. https://doi.org/10.1093/ijlct/cty039

Zhang Y, Guo W, Chen H, Gao J, Xu Z, Tao L, Li Z, Xu W (2019) Spinetoram confers its cytotoxic effects by inducing AMPK/mTOR-mediated autophagy and oxidative DNA damage. Ecotoxicol Environ Saf 183:109480

Zhou S, Liu J, Xu M, Lu J, Sun N (2015) Accumulation, availability, and uptake of heavy metals in a red soil after 22-year fertilization and cropping. Environ Sci Pollut Res 22:15154–15163

Zyoud SH, Sawalha AF, Sweileh WM, Awang R, Al-Khalil SI, Al-Jabi SW, Bsharat NM (2010) Knowledge and practices of pesticide use among farm workers in the West Bank, Palestine: safety implications. Environ Health Prev Med 15:252–261

Plant Biotechnology for Agricultural Sustainability

12

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Abstract

Plant biotechnology is an essential tool that allows agriculture improvement by increasing food production through tissue culture, molecular biology, and crop improvement. At present, agriculture is facing many problems that affect food production seriously; some of these problems are degradation of soils, salinity, contamination with heavy metals and hydrocarbons, drought, desertification, deforestation, and one of the solutions is biotechnology. This chapter will discuss aspects related to sustainable agriculture and food challenge, plant biotechnology, and plant biotechnology and sustainability. First, the incidence of agriculture is analyzed, on the one hand, in the reduction of hunger, and on the other, in the degradation of the environment, which can only be resolved through a sustainable model. Secondly, the most relevant applications of modern biotechnology in the accelerated propagation of plants, germplasm conservation, and genetic improvement are described. Next, both elements are linked, and it is analyzed how biotechnology can contribute to sustainability through modern technologies. The contribution of modern biotechnologies to sustainability in agriculture is illustrated through the presentation of examples of work done with the genus *Lupinus*. This genus comprises species useful for sustainable agriculture, which serve as a source of proteins and secondary metabolites, as well as in crop rotation. This chapter shows some of the results achieved in the multiplication and in vitro conservation of species from *Lupinus*, as examples of the application of biotechnology with an environment friendly approach.

Keywords

Agriculture · Environment · Food security · Sustainable · Tissue culture

Abbreviations

2,4-D	2,4-dichloro phenoxy acetic acid
AFLP	Amplified fragment length polymorphism
BA	Benzyladenine
Bt	*Bacillus thuringiensis*
CH	Casein hydrolysate
CRISPR	Clustered regulatory interspaced short palindromic repeats
DCR	Douglas-fir cotyledon revised
$g\ l^{-1}$	Grams per liter
GM	Genetic modified
GMCs	Genetically modified crops
GMOs	Genetically modified organisms
H_2SO_4	Sulfuric acid
IAA	Indoleacetic acid
IBA	Indol-3-butyric acid
ITS2	Internal transcribed spacer 2

kg ha^{-1}	Kilograms per hectare
Kin	Kinetin
mg l^{-1}	Milligrams per liter
MS	Murashige and Skoog
NAA	Naphthaleneacetic acid
PCR	Polymerase chain reaction
PPT	Glufosinate ammonium
RAPD	Randomly amplified polymorphic DNA
RFLP	Restriction fragment length polymorphism
RNA	Ribonucleic acid
SI	Sustainable intensification
SSN	Sequence-specific nucleases
SSRs	Simple sequence repeats
TAL	Transcription-activator-like
TALEN	Transcription-activator-like effector nucleases
TDZ	Thidiazuron
ZFN	Zinc-finger nucleases
μg l^{-1}	Micrograms per liter

12.1 Introduction

The world population on this planet is expected to a continuous increase from 6.7 billion to 9 billion by 2050. To fulfil the food demand, that will increase, the agricultural production needs to rise by 50% by 2030 (Royal Society 2009). It is also vital to notice that arable lands are limited because part of them are used for urbanization, or lost by abiotic stresses such as salinization, desertification, drought. The water needed for drink has also decreased in the past 60 years (United Nations Environment Programme 2002). The majority of the loses mentioned together with the loses caused by biotic factors (pathogens) occurs after the plants are entirely grown because at this point most or all of the land and water required to grow a crop has been invested (Dhlamini et al. 2005).

One solution to solve those problems is genetic improvement of crops, where new crops can be created with resistant to increasing temperatures, less water, flooding, salinity, pathogen, and insect (Gregory et al. 2009; Royal Society 2009). Biotechnology is an important technology that supports the protection and preservation of the environment by, for example, reducing the application of chemical pesticides and herbicides. Some plants have been genetically engineered to clean up heavy metal pollution from contaminated soil (Bagwan et al. 2010). The ecological point of view of biotechnology includes the application of several technologies including farming, agroindustry, forestry, fishing and aquaculture, and different objectives such as conservation of genetic resources, the diagnosis of several diseases of plants, and the production of fermented foods (Bagwan et al. 2010; Dash et al. 2016). This chapter aims to describe the importance and challenge of biotechnology as a sustainable agricultural resource.

12.2 Sustainable Agriculture and Food Challenges

12.2.1 Sustainable Agriculture

Sustainability in agricultural systems as a definition may include terms as agroecology, biodynamic, ecology, organic supply, sensitivity to the environment, low input and some others (McNeely and Scherr 2003). Some of the main principles for sustainability are (Pretty 2008):

a. The food production process is mainly taking account the nutrient cycle in plants, nitrogen fixation, regeneration and conservation of the soil, pathogens, predation, and parasitism;
b. To preserve the environment through the minimal use of non-renewable resources;
c. To use wisely what farmers know and the skills of them, and;
d. To use the knowledge and capacities of the people to solve the main problems of agriculture and natural resources, for example, plant pathogens, water, soil, and others.

According to Dobbs and Pretty (2004) and MEA (2005), sustainability mainly implies the use of technology to increase crop productivity without damage to the environment for agricultural systems. The principal objective of agriculture must be the maintenance of sustainable development to guarantee food safety for the population of the world not only today but also in future too. It is crucial to stand out sustainable agricultural development activities for the preservation and maintenance of natural resources; but at the same time, these resources must increase for future generations taking an account the increase in food demand and also the world population that in 2050, according to predictions, will reach nine billion peoples. Also, abiotic stress events such as drought, floods, scarce rain, salinity are growing, and they will decrease food production (Hans and Colaco 2019).

In sustainable agriculture, the systems include social and human resources at high levels (Olsson and Folke 2001; Pretty and Ward 2001). It does not imply the decrease or reduction in the use of resources (more land is needed to produce the same quantities of food). Some shreds of evidence indicate that sustainable agriculture initiatives and projects arise from modifications in some factors like use of fertilizers in several crops, pesticides and biological control, and so on (Buttel 2003; Tegtmeier and Duffy 2004). Agriculture has great importance in sustainable development, and hunger and poverty eradication. Sustainable agriculture must avoid soil degradation, guarantee biodiversity protection and conservation and achieve social and economic welfare (Hans and Colaco 2019).

12.2.1.1 Challenges and Proposals of the Food Security

The actual world crisis in food is caused mainly for the inequality in the access and distribution of food. It means that regardless of the overproduction of food in all countries, the hunger situation is still critical, with many people in this condition

(FAO 2011; CINU 2011). According to FAO-FIDA-PMA (2014), several millions of people suffer from hunger in the world, while many billion tons of food is wasted every year (Gustavsson et al. 2011; FAO 2014a). The enormous food waste (54%) happens in the first stages of post-harvest, management, and storing, and the rest (46%) occurs in processing, delivery, and consumption of food (Parfitt et al. 2010; Meena et al. 2018).

The growth of world population is globally slowing down, but in Africa and Asia, the population continues to increase. Many communities depend on agriculture for employment and income generation, and they cannot further develop by pressure to which the lands and water resources are already subjected (FAO 2017). Another challenge for the present and future agriculture is the deforestation caused mainly by the expansion of the agricultural lands. Almost half of the forests that once covered the planet have disappeared, and the underground waters run out quickly. The biodiversity has been severely eroded every year; one of the principal causes is the emission into the atmosphere of billions of tons of greenhouse gases, whose consequences are global warming and climate change (FAO 2017).

Agricultural systems or agroecosystems have a variety of properties that characterize them as modified ecosystems (Dalgaar et al. 2003; Swift et al. 2004). Some of these properties are (Gliessman 2005):

a. Productivity that is medium in healthy ecosystems, high in modern ecosystems, medium (possibly high) in sustainable agroecosystems;
b. Species diversity that is high in healthy ecosystems, low in modern ecosystems, medium in sustainable agroecosystems;
c. Functional diversity that is high in healthy ecosystems, low in modern ecosystems, medium-high in sustainable agroecosystems;
d. Output stability that is medium in healthy ecosystems, low-medium in modern ecosystems, high in sustainable agroecosystems;
e. Biomass accumulation that is high in healthy ecosystems, low in modern ecosystems, medium-high in sustainable agroecosystems;
f. Nutrient recycling that is closed in healthy ecosystems, open in modern ecosystems, semi-closed in sustainable agroecosystems;
g. Trophic relationships that are complex in healthy ecosystems, simple in modern ecosystems, intermediate in sustainable agroecosystems;
h. Natural population regulation that is high in healthy ecosystems, low in modern ecosystems, medium-high in sustainable agroecosystems;
i. Resilience that is high in healthy ecosystems, low in modern ecosystems, medium in sustainable agroecosystems;
j. Human displacement of ecological processes that is low in natural ecosystems, high in modern agroecosystems, low-medium in sustainable agroecosystems;
k. Sustainability that is high in natural ecosystems, low in modern agroecosystems, and high in sustainable agroecosystems.

According to Haberl et al. (2004) and Firbank et al. (2006, 2008), systems of modern agriculture have modified some of the above characteristics to increase production. Sustainable agroecosystems, on the contrary, need to change some of those properties to the natural systems without sacrificing productivity. It is necessary to maximize the renewable sources of energy and some energy flows that are directed to feed trophic essentials interactions to reach the goal of sustainability and maintain other ecosystem functions.

12.2.1.2 Agricultural Productivity in a Sustainable Way

Since 2005, several farmers are practicing integrated farming that is a step to sustainability, because they found that this system is safer in buying and supplying, while many moderns farming systems are inefficient (wasteful) (EA 2005). By adopting integrated farming practices, waste is less and the benefit to the environment is higher; so, farmers can save inputs by replacing regenerative technologies with external contributions, such as legumes or organic fertilizers for inorganic or biological control for pesticides (Pretty and Ward 2001).

Ostrom (1990) and Pretty (2003) declare that sustainable agroecosystems, as some relevant characteristics, have progressive effects in assisting to construct natural capital, strengthen populations (social capital), and improve human abilities. Examples of this include (according to Pretty 2008):

- Enhancements to usual investment that include increased water maintenance in soils, drinking water availability in the waterless period, and reduced soil erosion by the combination of organic matter;
- Improvements to social investment that include more public groups that are stronger, several new procedures to work with communal natural resources, and connections to some outside strategy organizations that are better;
- Improvements to human capital, increasing local capacity to face problems, the status of women, respect for marginalized groups, improving child health and nutrition, more employment and reversed migration.

Agricultural sustainability, in a conventional way, may involve a reduction of some inputs (fertilizers, water, pesticides) but the requirement of land is higher to produce the same amount of food that other systems—such as organic ones—where they may have lower yields but an increase of positive impact on natural capital. Some pieces of evidence show that active agricultural projects in agricultural sustainability arise from changes in factors of agricultural production (Tilman et al. 2011; Meena et al. 2019). In this sense compatibility between definitions of "sustainable" and "intensification" was suggested in the 1980s (Raintree and Warner 1986), and "intensification" became synonymous of harm in agriculture to produce food (Conway and Barbier 1990). Similarly, "sustainable" implies to the people good agriculture (Royal Society 2009). According to the Royal Society (2009), sustainable intensification (SI) is defined as a process or system where productivity (yields) increases without damaging the environment and using less land for cultivation. The definition is not a close concept, so any favoritism is made to any interpretation or vision of agriculture (Smith 2013), and both definitions (SI and "agricultural intensification") can be differentiated by priorities and goals than only to determine productivity improvement. Sustainable intensification based on Smith (2013) includes several options like the application of new technologies and improving the efficiency of current crop production, so for SI, the following aspects are to be considered:

- The mechanism in agriculture that increases the productivity of crops are: (a) better nutrient supply according to plant needs; (b) to improve recycling of nutrients; (c) to improve the use of the soil by reducing erosion, increase fertility, nutrients improvement; (d) to improve the use of crops according to bioclimatic regions.
- It is expanding the limits of crop production by using molecular techniques that will allow obtaining new crops more quickly compared to the past, making this possible without the increase of water use and intensity in fertilizing.

The SI has several advantages, going from climate change mitigation (reduced soil erosion and emissions from processes like nitrification), environmental improvement through the reduction in the use of fertilizers and pesticides (innovation, application of new technologies, transfer of knowledge), and social sector (Pretty et al. 2011).

12.2.2 Sustainable Agriculture in Latin America

Agriculture is one of the main productive activities in Latin America, where it constitutes a primary source of food and raw materials for various industries. To a greater or lesser extent, all the original peoples that populated the American continent before the arrival of the first Europeans were farmers, and there was an outstanding development of the forms of agricultural production in the territories that today occupy countries such as Mexico, Peru, Ecuador, and Bolivia. However, agrarian production techniques were transformed to the extent that European practices were introduced in Latin American agriculture, although traditional production practices were maintained in all countries of the area.

In the second half of the twentieth century, the growing need for food led to the implementation of the "Green Revolution" practices, among which are the new varieties of plants arising from genetic improvement, mineral fertilizers, synthetics pesticides, agricultural machinery of all kinds, irrigation systems, and other technologies (Gliessman 2013; Meena et al. 2020a, b). In the last 30 years, new products of science and technology have been incorporated; these include genetically modified organisms (GMOs) that in 2016 already occupied 185 million hectares (ISAAA 2016). The application of these intensive technologies has undoubtedly led to an increase in product volumes and yields per unit area. However, the criteria for their use have not always been based on scientific recommendations, but on guidelines imposed by the market, which have as a paradigm the sale of their formulations with the recommendation of a supposed excellent result. In South America, for example, the consumption of fertilizers and

Table 12.1 Fertilizer and pesticide consumption in the countries of South America (Adopted, Héctor et al. 2018)

Country	Fertilizer consumption (kg ha^{-1}) Nitrogen fertilizers (1)	Phosphoric fertilizers (2)	Potassium fertilizers (3)	Total fertilizers (1+2+3)	Pesticide consumption (kg ha^{-1})
Argentina	25.65	18.47	0.82	44.94	6.55
Bolivia	5.09	2.30	1.30	8.69	7.96
Brazil	45.23	51.22	59.55	156.00	NA
Chile	243.77	68.77	39.93	352.47	11.36
Colombia	150.55	72.64	68.62	291.81	13.46
Ecuador	70.11	13.11	40.81	124.03	6.85
Guyana	14.26	11.31	0.60	26.17	0.90
Paraguay	25.21	44.67	35.47	105.35	NA
Peru	55.82	20.79	14.05	90.66	3.09
Surinam	142.18	21.23	20.66	184.07	14.40
Uruguay	28.98	39.30	31.56	99.84	9.44
Venezuela	87.69	22.46	31.38	141.53	NA
AVERAGE	74.54	32.18	28.72	135.46	

NA not available

pesticides is excessive (Table 12.1). Countries such as Brazil, Chile, Colombia, Suriname, and Venezuela contribute to raising the average consumption of fertilizers in the subcontinent. In particular, Chile triples the total volume of fertilizers applied in South America, and the amount of nitrogen fertilizers used in its agriculture (243.77 kg ha^{-1}—kilograms per hectare) is comparable to that of China, which reaches 296.8 kg ha^{-1} (FAO 2014b). Even the figures of seemingly small consumption of countries such as Bolivia and Guyana do not reflect the reality since the amount of chemical inputs applied is not proportional to the amount of agricultural land in the countries of the region (Héctor et al. 2018; Meena et al. 2020a). Chile, Colombia, and Ecuador are also the countries in the area that most pesticides apply, with more than 10 kg ha^{-1} of these dangerous synthetic products.

Intensive practices in agriculture, such as mechanization and the use of excessive synthetic chemicals, lead to physical and chemical degradation of soils. Among the effects that occur are: the decrease in organic matter content, which is very degraded lands can be reduced to levels four times lower than usual (Mor-Mussery et al. 2015); the increase in the sandy fraction of the soil, with loss of cation exchange capacity and increase in saturation by aluminum (Reichert et al. 2016); the loss of nutrients and the immobilization of others (Casierra and Aguilar 2007); the reduction of the arable layer and the water retention capacity (Bestelmeyer et al. 2015), and other effects.

Undoubtedly, the growing population must be fed, and for this, a proportional supply of food is needed whose primary source is agriculture. However, the indiscriminate exploitation of soils, water sources, and other natural resources can only lead to their depletion, and consequently to the loss of the productive capacity of the

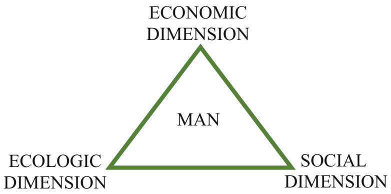

Fig. 12.1 The three dimensions of the sustainability triangle (Modified, Dyllick and Hockerts 2002)

planet, with the gradual extinction of life. Amid this concern, the concepts of sustainability and its application to agriculture emerge. Concerns for the preservation of the environment date from the mid-twentieth century, but approaches to development in terms of sustainability are attributed to the "Brundtland Report" (Brundtland 1987) in which the relationship between development and environmentalism is first raised. From this postulate, two trends developed: the so-called *weak sustainability*, which advocates economic growth over ecological protection, and *strong sustainability*, which reverses the equation giving preponderance to environmental conservation over advances in the economy (Norton 1995). Subsequently, Dyllick and Hockerts (2002) proposed that sustainability should be developed in three equivalent dimensions (economic, ecological, and social). A triangle with three dimensions, whose center is man, as the managing agent of the three aspects of sustainability, and also as a beneficiary of them, could be see in Fig. 12.1.

Apparently, from what is presented in Fig. 12.1, a definition of sustainable agriculture could be reached with relative ease, considering it as an agricultural production system in which economic and social benefits are obtained without affecting the environment. However, as noted by Velten et al. (2015), the picture is much more complicated. From a bibliographic analysis of journals dedicated to the topic of sustainable agriculture, these authors found that:

a. Although—in general—the three dimensions proposed by Dyllick and Hockerts (2002) are present in the sources consulted, these tend to focus more specifically on any of them.
b. Organizations that work for sustainable agriculture have diverse strategies.
c. Sustainable agriculture is present in several fields of action.

Table 12.2 shows the elements detected by Velten et al. (2015).

The concept of sustainability in agriculture, based on these trends, has evolved into a multifunctional agricultural production system. This should not be only a supplier of food and raw materials, but also a generator of multiple benefits in the area of ecosystem services, with resulting collateral activities such as biodiversity recovery, landscaping, and tourism (Huang et al. 2015). In Latin America, a stream of thought has been developed that defends the sustainability of agroecosystems based on a powerful ecological component. Authors such as Altieri and Nicholls (2017) consider Latin America as the area where agroecology emerged in the late 1970s and 1980s, strengthened by intellectual currents of a sociocultural nature. This

Table 12.2 Goals, strategies, and areas of action of sustainable agriculture (Adapted, Velten et al. 2015)

Goals	Strategies	Fields of action
• Environmental (production- and non-production specific)	• Adaptive management	• Agrifood system
• Social	• Cooperation	• Management and technological solutions
• Economic	• Ecology-based	• Social and environmental challenges
	• Economics-based	• Social and human capital
	• Holistic and complex systems thinking	• The social, political, and economic environment
	• Knowledge and science	
	• Subsidiary	

trend predominates in the area and has been strengthened through the influence of intellectuals, universities, non-governmental organizations, peasant movements, and other social organizations. However, much depends on government policies, while these are decisive when implementing massive strategies that can be accessible to small producers and guarantee a space where they can compete with the great companies that support the mode of production for conventional agriculture (Altieri et al. 2012; Yadav et al. 2020). Latin American political instability allows us to see a particularly complex scenario, in which the predominance of ancestral agricultural practices or new technologies, or of the complementation between the two, will depend more on power struggles between political groups and business interests than on the benefits that both trends can bring to the economy, the preservation of the environment, and social benefits.

12.3 Plant Biotechnology

12.3.1 Plant Tissue Culture

Tissue culture is the cultivation in the artificial nutrient medium of explants (any part of the plant, namely roots, stem, leaves, seeds, or protoplasts) under aseptic conditions (Touchell et al. 2008; Levitus et al. 2010). The first idea of growing an individual plant in the artificial medium was of Gottlieb Haberlandt in 1902. Haberlandt never realized the relevance of his approach, but more than 100 years after, this definition is still an essential tool for plant sciences (Touchell et al. 2008). Tissue culture is used for an increasing number of purposes such as crop improvement programs, embryo rescue, haploid and dihaploid production within a short time (Abraham 2009), species conservation, and rescue of species in danger of extinction. Plant propagation through tissue culture has several advantages compared to conventional propagation; according to Dominguez et al. (2008) these advantages are:

a. It is a propagation system based in cloning, which means that all the genotypic characteristics of the original material are maintained.
b. The entire process is carried out in a laboratory under controlled environments, totally independent of external conditions; so, the material is not affected by the seasonal changes during the year, drought, frost, high temperatures, or other environmental factors.
c. Around 10,000 plants can be obtained in a little time from a single donor.
d. The space required is minimal, and the time in which the process can take place is relatively short.
e. The plants obtained are free of phytopathogenic bacteria, fungi, and nematodes, and with more specific techniques (like meristems culture) plants can be free even from viruses and viroids.

"Totipotency" is the physiological base of the tissue culture and is defined as the capacity of any part of the plant to regenerate a whole plant in a basal medium. Tissue culture develops protocols for plant regeneration (thousands of plants from a piece of root, leaves, buds, and seeds) free of pathogens and with good yield (Yildiz 2012).

12.3.1.1 Micropropagation

The plant and the selected explant are significant for micropropagation because it is a cloning technique. The genotype of the plant is determinant since not all the plants have the same regeneration capacity. Some dicotyledon plants have an excellent regeneration capacity; meanwhile, woody plants such as fruit trees, pines, and some others are hard to regenerate (Pierik 1987). Species from *Lupinus* genus, such as *Lupinus campestris* L. and *Lupinus montanus* L. from the family Fabaceae, are known for having seeds with sturdy seminal covers, so several scarification treatments are used. The same procedure is used with *Acacia farnesiana* (L.) Wild, which belongs to the same family (Fig. 12.2) (unpublished results).

Explants should be isolated from healthy plants. Also, it is essential to notice that the regeneration capacity of mature tissues is quite low, such as the plant seeds in a resting stage (dormant) (Pierik 1987). There are several types of research in micropropagation of many different plant species. In the Center for Basic Sciences of the Autonomous University of Aguascalientes, projects have been developed aimed to establish methodologies for cultivation and propagation *in vitro* of several species from the genus Agave. The selection of species is based on their possibility of mezcal and pulque production, as is *A. cupreata*, *A. karwinskii*, *A. palmeri*, *A. potatorum*, and *A. salmiana*. Some other were selected for their ornamental value as *A. bracteosa*, *A. chiapensis*, *A. difformis*, *A. nizandensis*, *A. obscura*, *A. ornithobroma*, *A. peacockii*, *A. titanota*, and *A. victoria-reginae*. In vitro propagation technique of all these species was based in basal meristems selection. Basal seedling segments germinated in vitro were cultured in nutrient media supplemented with cytokinins such as benzyladenine (BA), 6-(γ,γ-Dimethylallylamino) (2iP), kinetin (Kin), thidiazuron (TDZ), and metaTopolin (mT). The efficiency of these systems goes from the production of averagely 2.2 shoots for each explant in

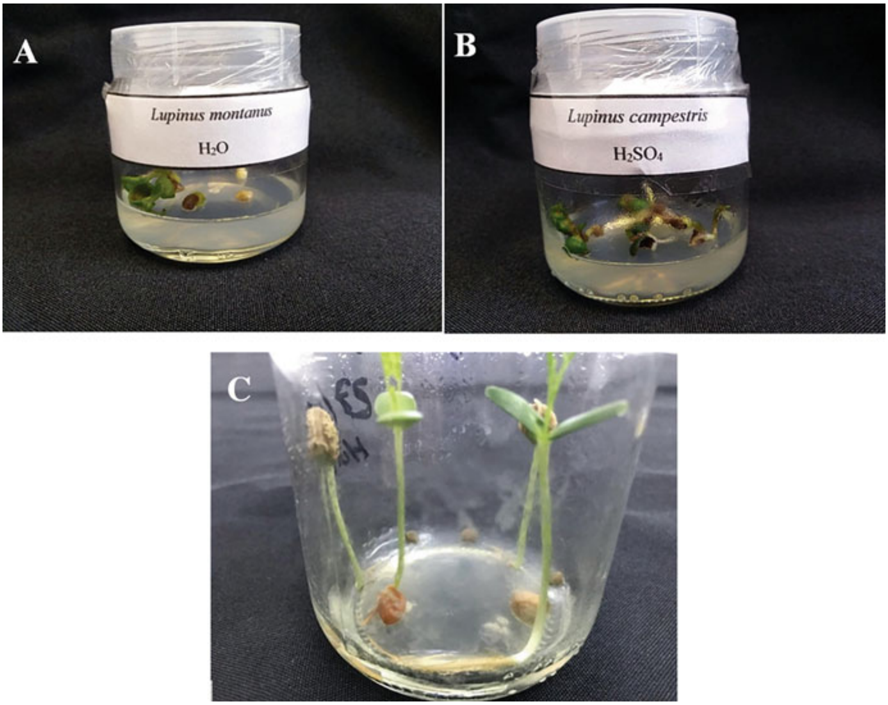

Fig. 12.2 Seed germination in the agar-water medium after scarification treatment, (**a**) *L. montanus*, boiling water for 24 h; (**b**) *L. campestris*, H_2SO_4 (sulfuric acid) for 15 min; (**c**) *A. farnesiana*, H_2SO_4 for 15 min

A. palmeri, up to 30 shoots per explant in *A. victoria-reginae*, in a propagation cycle of 40–60 days (Dominguez et al. 2008).

The morphogenesis of several cultivars of tomato (*Solanum lycopersicum* L.) was tested with the application of different antibiotics (carbenicillin, kanamycin, ampicillin, and cefotaxime). Murashige and Skoog (1962) was used for the experiment and the vegetable material used was cotyledons. As results kanamycin caused damage to explants and carbenicillin and ampicillin (100–400 mg l^{-1}) induced the regeneration of bud and non-toxic effect (Gerszberg and Grzegorczyk-Karolak 2019).

Research in *Cymbopogon schoenanthus* subsp. *proximus* used as renal antispasmodic was done by Abdelsalam et al. (2018). They studied the influence of several phytohormones (naphthaleneacetic acid—NAA, BA), different carbon sources, methyl jasmonate, and vitamins. The higher callus induction (100%) was obtained with 4 mg l^{-1} NAA combined with 0.5 mg l^{-1} BA; when NAA was used at 1.0 and 4.0 mg l^{-1} combined with 0.5 mg l^{-1} of BA the number of shoots increased; also, 6% sucrose induced root induction efficiently and sugar at 3% had a good effect increasing shoot numbers. Different concentrations of methyl jasmonate, biotin, and calcium pantothenate were used for root formation, but shoot induction was reduced.

Ramirez-Mozqueda and Iglesias Andreu (2017) studied friable calluses in *Vanilla planifolia*. Immature seeds were cultured in MS medium supplemented with 0.45 μM TDZ, and friable callus was obtained. The effect of another growth regulator (BA) was evaluated in different concentrations with the same culture medium but without gelling agent (liquid) supplemented with 8.88 μM BA, a 0.5 g of inoculum density was obtained and at 16 days the growth of the cell suspension culture was high, with 80% cell viability.

12.3.1.2 Callus Culture

The main objective of using callus (a mass of undifferentiated cells, Fig. 12.3) is to develop an efficient, fast, and large-scale micropropagation methodology, as well as to induce and generate plant structures that, due to their characteristics of totipotence, undifferentiation, and regeneration capacity, allow the development and implementation of modern biotechnological techniques for the non-traditional genetic improvement.

A research was done with *Vanilla planifolia* Jacks. ex Andrews (*Orchidaceae*) to develop a massive, efficient, and fast propagation methodology. The calluses were formed from an undifferentiated and transient structure generated from the radical

Fig. 12.3 Callus from in vitro root of Lupinus species (Unpublished results)

apices grown in the absence of light, in a liquid MS medium supplemented with 30 g l^{-1} (grams per liter) sucrose, 1 mg l^{-1} BAP, and 1 g l^{-1} of hydrolyzed casein. The highest percentage of calluses (72%, $p < 0.05$) was formed in solid MS medium supplemented with 0.5 mg l^{-1} of 2,4-dichloro phenoxy acetic acid (2,4-D) in the dark (Gätjens-Boniche et al. 2018).

Callus obtained through in vitro culture allow the production of secondary medicinal metabolites and three varieties of *Artemisia annua* L., an aromatic Asteraceae plant, were cultured with this aim. Plant leaves were cultured in MS medium supplemented with (a) 0.5 mg l^{-1} BA, 0.5 mg l^{-1} NAA, 0.5 g l^{-1} casein hydrolysate (CH), (b) picloram (0, 0.5, 1.0, 1.5, and 2.0 mg l^{-1}), and (c) 2,4-D (0, 0.5, 1.0, 1.5, and 2.0 mg l^{-1}). The highest callus formation was accomplished in MS medium with 0.5 mg l^{-1} BA, 0.5 mg l^{-1} NAA, and 0.5 g l^{-1} of CH. Calluses observed on 0.5 mg l^{-1} picloram were more easily dispersed than calluses from other media (Keong et al. 2018).

In mango (*Mangifera indica* L.) var. Ratnagiri, nucellar tissue was used to induce somatic embryogenesis. The MS medium was supplemented with five TDZ concentrations (0.45, 2.27, 4.54, 9.08, and 11.35 μM), alone or combined with 4.52 μM 2,4-D, without any other plant growth regulators. After 4–9 weeks, a medium with 4.52 μM 2,4-D and 2.27 μM TDZ (induction medium) was used for somatic embryos. A total of 35 somatic embryos per gram of fresh weight can be obtained after several weeks (Malabadi et al. 2011a).

Somatic embryogenesis is the formation of an embryo from a somatic cell, without the need of gamete fusion (Tisserat et al. 1979). According to Yeung et al. (1996) this method, theoretically, is the most efficient for the mass production of plants in vitro due to the bipolar nature of the embryo, the possibility of the entire automation of production process, and the high multiplication coefficients in short periods. Its disadvantages lie in the lack of knowledge about the parameters that regulate this process; thus, the number of species in which efficient somatic embryogenesis allows productive use of the method is still limited. Malabadi et al. (2011b) used immature zygotic embryos of several commercial varieties of papaya (*Carica papaya* L.) for the obtaining somatic embryos in an MS medium supplemented as described by Malabadi et al. (2011a) with similar results. Concerning the varieties used, the authors found the best results of somatic embryogenesis in Taiwan-786 (87.0 ± 4.2), followed by Taiwan-785 (85.0 ± 3.0) and Coorg Honey Dew (81.0 ± 3.2).

Malabadi et al. (2004) worked with apical dome section of *Pinus kesiya* Royle ex Gordon. The goal of the research was the initiation, maintenance, and maturation of somatic embryos. The apical dome section was cultivated in half and full strength DCR (Douglas-fir cotyledon revised) (Gupta and Durzan 1985) basal medium supplemented with 0.2 g l^{-1} polyvinyl pyrrolidine (PVP), 7 g l^{-1} agar (Difco-bacto), 30 g l^{-1} maltose, and 0.2, 0.3, or 0.4% activated charcoal without growth regulators. Explants were incubated in the dark at 4 °C for 1–10 days. Another culture condition was the application to the basal medium for three days of 0.3% activated charcoal at different temperatures (10, 15, and 20 °C). For the initiation stage of embryogenic callus several concentrations of indoleacetic acid (IAA), indol-3-butyric acid (IBA), NAA, and 2,4-D with Kin and BAP were used in half and full strength (inorganic salts) DCR basal media. The maintenance phase was done with callus showing pro-embryonal masses in half of basal DCR medium containing 40 g l^{-1} maltose, 4 g l^{-1} gellan gum supplemented with 2.26 μM 2,4-D, 2.68 μM NAA, and 0.88 μM BA. A desiccation treatment was used after maturation stage where a half-strength DCR basal medium with 60 g l^{-1} maltose, 37.84 μM abscisic acid (ABA), and 5 g l^{-1} gellan gum was used. The use of NAA in the medium for callus induction produced light white embryogenic callus, whereas the mixture of NAA, 2,4-D, and BA produced white friable embryogenic callus when apical dome sections were cultured on half DCR basal medium. In the maintenance medium, 79.2% of the shoot produced somatic embryos on 2 g l^{-1} gellan gum, while 1, 3, 4, and 5 g l^{-1} of gellan gum formed less than 7% of somatic embryos.

12.3.1.3 Plant Regeneration

Propagation of plants through plant tissue culture is very useful (Hammschlag et al. 1995). Callus production with *in vitro* techniques and plant regeneration are the first stages for plant manipulation (Islam et al. 2005). A research was carried out with *Sorghum bicolor* (L.) Moench variety Róna 1. As plant material, seeds were germinated for the obtaining of shoot tips and a basal medium used was MS supplemented with 2,4-D, Kin, proline, vitamin C, sucrose, and Bacto™ Agar. For the determination of the induction and regeneration of potential of calluses, the control medium was supplemented with CH, polyvinylpyrrolidone, honey, and sucrose; the explants were incubated in the dark. The best callus induction (80.0%) was obtained in the medium supplemented with honey and sucrose. For plant regeneration MS medium was also used with two treatments: (1) BAP and sucrose at 2.0 mg l^{-1} and 30 g l^{-1}, respectively, and (2) BAP and sucrose at 2.0 mg l^{-1} and 15 g l^{-1}, respectively, with honey (15 g l^{-1}). The medium with sucrose and honey led to better shoot regeneration from the calluses (Dreger et al. 2019).

Iriawati and Rodiansyah (2017) used basal shoot explants from 10-day old seedlings for the in vitro regeneration of foxtail millet (*Setaria italica* (L.) Beauv.). Basal MS medium was supplemented with two different concentrations of 2,4-D, Kin, 6 BAP, and 1.5 mg l^{-1} nickel sulfate ($NiSO_4$). The best shoot induction was achieved in MS basal medium supplemented with 0.5 mg l^{-1} Kin, 2 mg l^{-1} 6 BAP, and 0.1 mg l^{-1} 2,4-D with 60% of explants developing direct shoot organogenesis. Several light treatments (provided by blue, green, yellow, red, and clear cellophane film covers) were used by Mohamed et al. (2017) for the in vitro regeneration, growth, and proliferation of strawberry (*Fragaria* sp.) plants. They used leaf discs for shoot regeneration. Leaf discs were cultured in MS medium supplemented with 3% sucrose, 0.7% agar plus 6.9 μM TDZ; for shoot proliferation, shoot tip explants from the cultivars FES, SW, TD, Camarosa (CAM), and Gaviota (GA) were collected from 6-week old plantlets after removal of all leaves and roots, and they were placed on a similarly supplemented MS medium with 1.32 μM BA. For the rooting phase, explants and cultivars as in shoot proliferation were placed on supplemented MS with 4.9 μM IBA. Red and green light led induced the best shoot regeneration (10 shoots explant^{-1}), and green light induced the highest frequency for shoot proliferation (15.3 shoots explant^{-1}). In the stage of root formation, the best results were obtained with white light followed by yellow or blue light. Blue and yellow light rendered high total chlorophyll content.

Balwinder et al. (2011) worked in an efficient protocol for *Citrus jambhiri* Lush. (rough lemon) using cotyledons as explants. They obtained a 91.66% of callus induction in MS medium supplemented with 2,4-D at 2 mg l^{-1} in combination with malt extract (ME) at 50 mg l^{-1}. For plant regeneration, calli were divided into small pieces and cultured in MS basal medium supplemented with BA at 3 mg l^{-1} where 87.50% of shoot regeneration was obtained. The regeneration and control of explants necrosis for an endemic tree of India named *Soymida febrifuga* (Roxb.) A. Juss., (Meliaceae) was investigated by Chiruvella et al. (2011). Nodal segments were cultured in MS basal medium supplemented with BA (2.0, 3.0, and 5.0 mg l^{-1}), Kin (1.0 2.0, and 3.0 mg l^{-1}), NAA (0.2 mg l^{-1}), and IAA (0.2 mg l^{-1}) with different combinations. The best result was observed with the combination in MS medium of BA (2 mg l^{-1}), and NAA (0.2 mg l^{-1}) where a frequency of 80.4% was obtained. The explant necrosis was controlled at 98% in MS medium supplemented with calcium nitrate (556 mg l^{-1}), calcium pantothenate (1.0 mg l^{-1}), activated charcoal (20 mg l^{-1}), and fructose (100 mg l^{-1}).

The species *P. kesiya* is a conifer of the family of the Pinaceae, specifically to the genus Pinus. Malabadi et al. (2005) worked with embryogenic cultures of this species using mature zygotic embryos with half of the MS germination basal medium with maltose, gellan gum, 2, 4-D and several concentrations of triacontanol (1, 2, 3 4, 5, 7, 10, 15, 20, 25, and 30 μg l^{-1}) where 10 μg l^{-1} (micrograms per liter) produced white-mucilaginous embryogenic callus. The white-mucilaginous embryogenic calli were subcultured in a medium with 2.0 μM 2,4-D and 2.0 μg l^{-1} triacontanol. Somatic embryos were cultured for germination in half-strength MS germination medium without growth regulators.

12.3.2 Plant Breeding

12.3.2.1 Marker-Assisted Selection

Genetic markers were used for the first time to determine the order of genes along chromosomes when Sturtevant (1913) made the first genetic map in *Drosophila melanogaster* (fruit fly). After that, Sax (1923) worked with *Phaseolus vulgaris* L. in the generation of gene linkage between seed color and size. Since those studies, genetic markers have changed from morphological traits to isozymes and finally to DNA markers; today they are used in many research areas such as plant breeding, characterization of plant germplasm, and others (Henry 2001). According to Jiang (2013) genetic markers can be classified into two categories: (1) classical markers where it is possible to find morphological markers, cytological markers, and biochemical markers and (2) DNA/molecular markers where some representative examples are: RFLP (restriction fragment length polymorphism), AFLP (amplified fragment length polymorphism), SSRs (simple sequence repeats), SNP (single-nucleotide polymorphism), and DArT (diversity arrays technology). Morphological markers, as the name said, are used to differentiated qualities that can be seen, like the color of the flower, the structure of different seeds, and so on, and they do not need biochemical and molecular techniques or instruments for their study. Their principal disadvantage is that they are few, and can be influenced by several environmental factors and growth stages of the plant (Eagles et al. 2001). For the research of plant variation, these markers have been used for plant breeding (Weeden et al. 1994).

In cytology, the structural characteristics of chromosomes can be shown by the chromosomal karyotype and bands. Band patterns, which are shown in color, width, order, and position, reveal the difference in the euchromatin and heterochromatin distributions. For example, the Q bands are produced by quinacrine hydrochloride, the G bands are produced by Giemsa staining, and the R bands are the inverted G bands. These chromosomal referents points are used not only for the characterization of normal chromosomes and the detection of chromosomal mutation but also for physical mapping and identification of linkage groups. Physical maps based on morphological and cytological markers laid the groundwork for mapping genetic links with the help of molecular techniques. However, the direct use of cytological markers has been very limited in genetic mapping and plant breeding (Jiang 2013).

Biochemical markers (isozymes) are enzymes codified by several genes but with the same functions. They were used effectively in genetic diversity detection within the structure of the population. The disadvantages of these markers are that they are few; also, the polymorphism they detect is weak, and they can be affected by extraction methods, tissues, plant growth stages, biotic and abiotic stress (Paterson 1996; Baird et al. 1997; Henry 1997).

Molecular markers are based in the polymorphism present among the nucleotide sequences of any individual. That is, they can indicate the genetic differences between species and organisms (Henry 1997). These markers are handy because of their abundance, their neutrality (they are frequently located in non-coding regions of deoxyribonucleic acid-DNA), and because they are not affected by environmental factors and/or the plant growing phase (Winter and Kahl 1995). Some molecular markers useful in plant breeding are:

a. *Restriction Fragment Length Polymorphism (RFLP)*: This was the first marker used, and it is the only one based on hybridization. This marker was created by Botstein et al. (1980), and the polymorphism is due to insertions/deletions, point mutations, translocations, duplications, and inversions. For this technique, the DNA is extracted, purified, and mixed with restriction enzymes to excise DNA at recognition sites. For this technique, the DNA is extracted, purified, and mixed with restriction enzymes to excise DNA at recognition sites and the results are visualized in agarose or polyacrylamide gel electrophoresis (PAGE) were several bands (fragments with different length) are separated (Ni et al. 2002).
b. *Polymerase Chain Reaction (PCR)-based markers*: Kary Mullis in 1983 developed a new technique that made possible the synthesis of large amounts of DNA from a fragment without cloning: polymerase chain reaction. With this procedure, it is possible to synthesize millions of copies in a couple of hours, having then a

sufficient amount to study a sequence of interest representing only a ten-millionth part within a mixture of DNA as complex as the human genome itself (Mullis 1990).

c. *Randomly Amplified Polymorphic DNA (RAPD)*: This analysis was described by Williams et al. (1990), and it is based in DNA amplification by PCR using a single, short (10 nucleotides), and random primers. The amplified fragment depends on the length and size of both the primer and the target genome. The absence or presence of the band is corroborated in gel electrophoresis, and this is the confirmation of the polymorphism (Winter and Kahl 1995).
d. *Amplified Fragment Length Polymorphism (AFLP)*: These markers are a combination of RFLP and PCR markers; DNA is digested, and then the PCR is implemented (Farooq et al. 1996). The AFLP has the advantage that sequence information is not needed, turning it into a cost-effective technique. Two restriction enzymes are used to excise the DNA, and the fragments are then joined at each end by complementary adapters and subsequently amplified by PCR; sizes finally separate the products by electrophoresis (Ni et al. 2002).
e. *Simple Sequence Repeats (SSRs) or microsatellites*: SSRs are tandem repeat motifs of 1–6 nucleotides that abound in the genome of various taxa from prokaryotes and eukaryotes (Hancock 1999). The microsatellites are distributed in coding and non-coding regions and are characterized by being highly polymorphic in terms of their length; therefore, they are suitable regions to be used as molecular markers at the population level (Zane et al. 2002). This high polymorphism level is due to a high mutation rate because events of deletion and insertion during DNA replication and this polymorphism can be easily detected by PCR (Schlötterer 2000; Mohler and Schwarz 2005).

Molecular markers are handy for the study of genetic diversity in several crops. Kumar et al. (2008) studied genetic diversity in several accessions of beans (*P. vulgaris*) using RAPD, and they found that 95% of the amplified products were polymorphic, demonstrating a right quantity of variation at the DNA level among these accessions. AFLP markers were used by Dehmer and Hammer (2004) for characterization of the genetic diversity between 44 accessions of the *Solanum nigrum* L. complex, and through this research, they were able to classify taxonomically unknown material and to correlate the clustering of the examined accessions with their geographic origin.

Several tomato determinate and indeterminate inbred lines were collected from different countries (China, Japan, South Korea, and the USA) and for the diversity analysis, 35 SSR markers were used. Gene distances between 0.72 and 1 rs showed diversity at a moderate level and a significant number of alleles that are unique (Benor et al. 2008). Microsatellites SSR were used for the identification of genetic variation and characterization of 46 parthenocarpic genotypes of round zucchini shrub type squash (*Cucurbita pepo* L.), and the polymorphic loci were 100% with five groups identified (Méndez-López et al. 2019).

12.3.2.2 Genetic Engineering

According to Shetty et al. (2018), genetically modified crops (GMCs) are plants to which the DNA was modified using genetic engineering techniques (addition, deletion, or manipulation of nucleotides or genes) to obtain a change or a desired characteristic that cannot occur in nature. The process of generating a genetically modified crop can be divided into six stages: (1) identification and characterization of the desired gene, (2) incorporation of the gene of interest in a suitable genetic construction, (3) introduction of the development in plant cells, (4) selection of transformed plants, (5) regeneration of the whole plant from transformed cells, and (6) incorporation of the new GMC as a commercial variety (Gutiérrez et al. 2015). Several efficient protocols and methods are available to create genetically modified crops. Plant transformation techniques offer the possibility of accessing an unlimited number of genes that were previously not accessible to plant breeders. Specifically, for gene transfer from non-sexually compatible species, significantly increasing genetic improvement options are open (Basu et al. 2010). Some of the methods used are:

a. *Agrobacterium tumefaciens* mediated transfer: This method is well established, and it uses the bacteria *Agrobacterium tumefaciens* or *Agrobacterium rhizogenes*. These bacteria contain a genetic element outside their chromosome, called the tumor-inducing (Ti) plasmid. The genes of biotechnological interest are introduced into the Ti plasmid so that the bacteria can transfer it into the plant. A segment is stably assigned to the chromosomes of the plant with which it is co-cultivated. This system can move large and intact parts of DNA with low copy numbers and stable integration. This method has been well tested in dicotyledonous plants like potatoes (*Solanum tuberosum* L.), tomatoes, and tobacco (*Nicotiana tabacum*) (Gutiérrez et al. 2015; Shetty et al. 2018).
b. Gene guns (Biolistic): This is a great method that uses gold or tungsten microparticles covered with DNA of interest, which is accelerated at high speed to the target tissues. The introduced DNA can reach the nucleus and insert stably. It is also possible to add sequences in chloroplasts or mitochondria for the expression of the proteins of interest in these organelles. This ability to transform organelles is very desirable in the generation of organisms expressing recombinant proteins or enzyme overproduction. Some disadvantages include low transformation efficiency and reported transgene-silencing due to multi-copy insertions (Shetty et al. 2018).
c. Clustered regulatory interspaced short palindromic repeats (CRISPR): This method uses short, repetitive base sequences present in segments of prokaryotic DNA, and the repetition is followed by a spacer DNA that is exposed to a foreign DNA (virus or plasmid) (Shetty et al. 2018).

The decision about the release of genetically modified plants is not directly related to commercialization because some of these plants have passed the regulatory procedures positively but never were released to the market (Baranski et al. 2019). Bt maize is a crop that expresses *Cry* protein, naturally produced by *Bacillus* *thuringiensis* (Bt; a bacterium used as an insecticide since 1938); it is toxic to stem borer insects that die when eating Bt corn leaves or stalks (Bates et al. 2005; Kumar et al. 2016a). Qaim (2009) summarized studies of impacts related to Bt cotton (*Gossypium* spp.) (resistant to insects) in three regions of India, finding an increase in productivity of 37, 33, and 24% due to the improvement of that character. A research was done by Du et al. (2019) to eliminate a marker (gene *egfp*) in transgenic maize using a heat-inducible auto-excision vector that combines a site-specific recombinase. Consequently, transgenic maize plants free of the marker were obtained. Waltz (2015) from J R Simplot company obtained a potato (Innate potato) resistant to blackspot bruising browning and with less content of asparagine (an amino acid that is converted into acrylamide when the potato is fried). Weeds that are not desired in agriculture are a problem; herbicides like Roundup™ and Liberty Link™ are used to eliminate those unwanted plants (Bahadur et al. 2015). Roundup ready™ soybeans (*Glycine max*) contain genes conferring tolerance to glyphosate (an herbicide that kills weeds). In this way, this herbicide can be used without damage the crop (Padgette et al. 1996).

12.3.2.3 Genome Editing

The technology of recombinant DNA is a method used for genetic engineering where the exact place of a changed fragment of DNA in a host organism is difficult to locate. In genetic transformation, expertise is necessary because for every sequence to cut a new specific molecule must be created. The new genome editing technology (CRISPR-Cas9) solves this problem: CRISPR-Cas9 cuts DNA in different places, and the cell itself repairs DNA, turning this technology into a faster, more comfortable, less expensive, and more accurate procedure (Habets et al. 2019).

The discovery of sequence-specific nucleases (SSN) allowed the creation of modification at the genetic level and the regulation of DNA sequences in several organisms (Doudna and Charpentier 2014; Barrangou and Horvath 2017). The SSN can be reprogrammed to produce DSBs (DNA double-strand breaks) at a desired genomic location. Until now, four main classes of protein have been used for an accurate edition of the genome: mega nucleases (Smith et al. 2006; Paques and Duchateau 2007); zinc-finger nucleases (ZFN) (Maeder et al. 2008); TALEN (Transcription-Activator-Like Effector Nucleases) (Bogdanove and Voytas 2011), and several endonucleases derivate from CRISPR-Cas (Abudayyeh et al. 2016, 2017). The technologies from the first generation (ZFN, TALEN, and mega nucleases) are excision DNA systems, and the CRISPR-Cas endonucleases are excision systems of DNA and RNA (Ribonucleic acid) guided by programmable RNA (Langner et al. 2018).

a. Meganucleases: Mobile introns encode these enzymes, and they happen naturally (Smith et al. 2006; Paques and Duchateau 2007). They can identify new DNA target sites. An example of these enzymes is the I-SceI meganucleases from yeast (best-characterized) used in genome editing (Voytas 2013).

b. ZFNs: According to Voytas (2013) and Puchta and Fauser (2014) they were the first endonuclease created for the recognition and cleave of chromosomal DNA, and they are artificial bipartite enzymes with a length of ~310 amino acids.
c. TALENs: They are derived from TAL (transcription-activator-like) effectors of the bacterial plant pathogen. The construction of a new TALEN is hard and expensive; also, it is not appropriate for multiple gene editing because of the large size and the requirement of two proteins needed to identify antiparallel DNA strands (Voytas 2013).
d. CRISPR-Cas9 Nucleases: This technology only needs two components: (1) An endonuclease (Cas9) from a monomeric DNA, and (2) a single RNA sequence that is a guide which binds to the DNA target (Steinert et al. 2015).

New CRISPR Nucleases: This system has five target nucleases from DNA and two target nucleases from RNA (Mitsunobu et al. 2017; Koonin et al. 2017). The function of some of the target nucleases from DNA was proved in vivo and in vitro (Burstein et al. 2017; Stella et al. 2017). The activity of Cpf1 (Cas12a) was authenticated in plants using Cpf1 orthologs from a bacterium *Francisella novicida* that belongs to the Francisellaceae family, which consists of gram-negative pathogenic bacteria (FnCas12a), *Lachnospiraceae bacterium* ND2006 from an anaerobic family (Lachnospiraceae) (Nogue et al. 2014) (LbCas12a), and *Acidaminococcus* sp. bacterium belongs to the phylum Firmicutes (AsCas12a). An evaluation between these nucleases revealed that LbCas12a is more efficient than AsCas12a and FnCas12a (Wang et al. 2017a).

Examples of the use of CRISPR-Cas9 technology are the works in maize (*Zea mays* L.) and potato to obtain modified crops with homogenous starch composition rather than a mixture (amylose or amylopectin, not both). Granule-bound starch synthase I (GBSSI), the key enzyme required for amylose synthesis, has been targeted in tetraploid potato plants by transfecting protoplasts with preassembled Cas9/gRNA RNPs (Shure et al. 1983; Andersson et al. 2018).

The obtainment of pathogens-resistant crops is an essential aim in plant improvement. Wheat (*Triticum* sp.) plants resistant to *Blumeria graminis* f. sp. *tritici*, the fungal pathogen responsible for powdery mildew disease is one example (Wang et al. 2014). Also, cucumber (*Cucumis sativus* L.) plants resistant to Potyvirus were obtained using CRISPR/Cas9 technology (Chandrasekaran et al. 2016). Finally, disease resistance has also been achieved by using CRISPR/Cas9 in Wanjincheng orange (*Citrus sinensis* Osbeck) plants to target the promoter of the susceptibility gene CsLOB1, resulting in plants with enhanced resistance to citrus canker (Peng et al. 2017). Agrobacterium, in the genome editing topic, is more used for the creation of transgenic crops, and several efficient protocols of transformation and regeneration of plant species exist. In this context, agrobacterium can be used in tobacco leaves to express the CRISPR/Cas9; this allowed the recovering of edited plants with the non-transgenic genome, so 17% of the edited plants with improved genome using this method were non-transgenic (Chen et al. 2018).

12.4 Plant Biotechnology and Sustainability

12.4.1 Biotechnology and Food Production

It is estimated that by 2050 the world population will increase by a third, and for this reason, agricultural production enhances up to 70% will be necessary. Also, the demand for food and forage crops will double over the next 50 years. In 2008, the World Bank estimated that around 10 million people die each year from hunger and food diseases (Dixon and Tilson 2010). An immediate and efficient solution to those problems is plant biotechnology. Plant biotechnology is responsible for generating sufficient and healthy food, in addition to the fact that it has managed to transform the agricultural techniques to enhance plant production by increasing crop resistance to weather changes, pests and diseases, and other (Espinoza 2018; Kumar et al. 2016a, b, 2019). More than 50 years after the start of the application of biotechnology in agriculture, it remains a discussion about its benefits and social costs. The main target of the accusations has been transgenic crops because of their possible impacts on the environment and society (Altieri 2003). Other "softer" technologies have suffered minor criticism.

For more than three decades, discussion about if biotechnology is compatible and can support or not sustainable agriculture has gone on. Believers in plant biotechnology as a tool to transform agriculture in a more sustainable process underline that biotechnology increases crop production increase, while environmental impacts related to agriculture are reduced (Brookes and Barfoot 2018). The largest companies that produce genetically modified seeds (Monsanto, Dow Agrosciences, DuPont, Syngenta, Bayer) explain that biotechnology supports sustainability in agriculture because production can be increased through it as well as farmer incomes, also biotechnology can reduce some environmental impact in agriculture (pesticides). Similarly, the use of plant biotechnology will allow obtaining new varieties that can survive and produce under stress situation such as salinity and drought (Scientific American 2009). Several professors and researchers at universities and government executives defend the fact that using genetic modification methods can be friendly with sustainable agriculture and, under right situations, could be consistent with organic farming (Ronald 2008; Ronald and Adamchak 2008).

Plant genetic resources are essential for humanity, as they constitute the source for genetic improvement and obtaining new varieties of plant species. However, anthropic activity has caused a negative impact that led to a significant decrease in wild germ plasma. In the period from 1996 to 2004, the alarming amount of 8321 plant species entered the Red List of threatened species of the International Union for the Conservation of Nature and Natural Resources. It is estimated that this number increases every year in proportions not always calculable (Sarasan et al. 2006). Although authors such as Rao (2004) point out the annual loss of more than 15 million hectares of tropical forest, it is difficult to appreciate how many species (even still unknown to humanity) disappear with them. Biotechnology can help with the protection of these endangered plant species by using tissue culture and the creation of in vitro germplasm banks.

One example of how useful plant biotechnology is for agriculture sustainability is the tissue culture of species from the genus. At present, 200–300 species form this genus have been described, and most of these live in American territory. Plants from this genus are associated with nitrogen-fixing bacteria. Lupinus synthesizes quinolizidine alkaloids (AQ) as part of a defense strategy against herbivores. Currently, Lupinus species find numerous applications, as a source of protein in food (Tapia and Fries 2007) and secondary metabolites with various biological activities (Fornasini et al. 2012), also improving the soil in crop rotation (Stepkowski et al. 2011). Another potential use of the species of the genus Lupinus is as green manure or in ecological restoration and reforestation programs (Ramírez-Contreras and Rodríguez-Trejo 2009). During the monitoring and collection of biological material, it was observed that the farmers of the Amecameca region in Mexico allow the establishment of Lupinus plants in their plots, as they “improve the crops.” To validate this practice, the effect of the incorporation of the biomass of a native species, *L. bilineatus*, into a nut orchard was evaluated; results evidence that it provides the same amount of nitrogen (N_2) as the chickpea, natural manure used by nut producers (Figueroa-Rodríguez 2016). At the same time, the diversity of beneficial bacteria associated with the rhizosphere of *L. montanus* was evaluated, finding the presence of the genera *Pseudomonas*, *Serratia*, *Rahnella*, *Plantibacter*, *Microbacterium*, *Pantoea*, *Staphylococcus*, *Arthrobacter*, *Paenibacillus*, and *Chryseobacterium*, which have a close correlation with the phenology of the plant (López-Jaimes 2014). However, Mexican species are not cultivated, so their use as a source of secondary metabolites is limited. The working group from the Instituto Politécnico Nacional, Universidad Autonoma de Chihuahua (Facultad de Ciencias Agrícolas y Forestales), and some other Mexican institutions initiated studies to achieve in vitro propagation of these species and the creation of a germplasm bank; recently, a Science Basic CONACyT project was approved to work on these topics. Some preliminary and unpublished results with *L. montanus* and *L. campestris* have been obtained in multiplication (6 BAP and Kin) and conservation (mannitol) (Fig. 12.4).

The seeds of the Lupinus genus species undergo physical dormancy. According to Rodríguez and Rojo (1997), the germination of the seed of *L. montanus* improves after the application of pre-germinative treatments to soften the seed coat. Some species of this genus such as *L. campestris*, *L. bilineatus*, and also *L. montanus* have been tested with scarification treatments such as boiling water, H_2SO_4, and cut off the seed. The best results (unpublished) achieved in a multidisciplinary project from the Universidad Autónoma de Chihuahua, Facultad de Agronomía (Dra. Sandra Perez Álvarez and Lic. Edgar Omar Carrasco Rivera), and the Instituto Politécnico Nacional (CEPROBI) (Dr. Kalina Bermudez Torres) were with H_2SO_4 by 12 min in *L. montanus* and by 15 min in *L campestris*, *L. bilineatus*, and cut off the seed in the laminar flow chamber (Fig. 12.5).

Biofortification is another application of biotechnology in agriculture that influences in sustainability. This technology is based on the application of

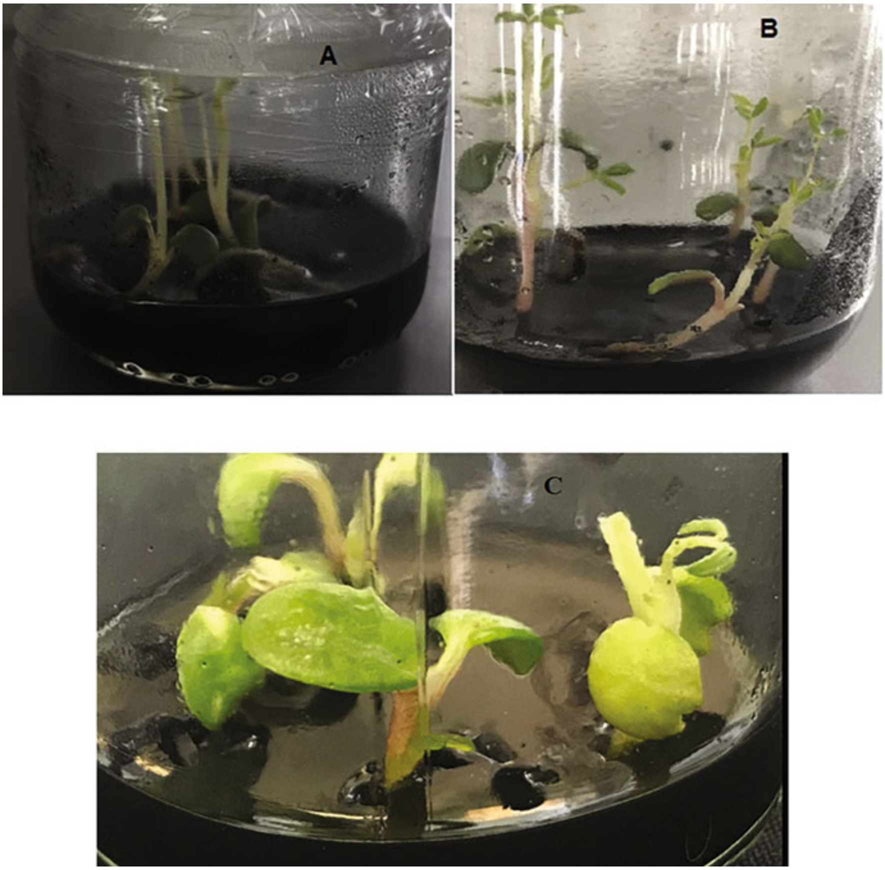

Fig. 12.4 Multiplication in MS medium supplemented with BAP 1 mg l^{-1} and kinetin (Kin) 0.5 mg l^{-1} and with activated carbon (**a**) *L. montanus*, (**b**) *L. campestris*, (**c**) Conservation medium with mannitol

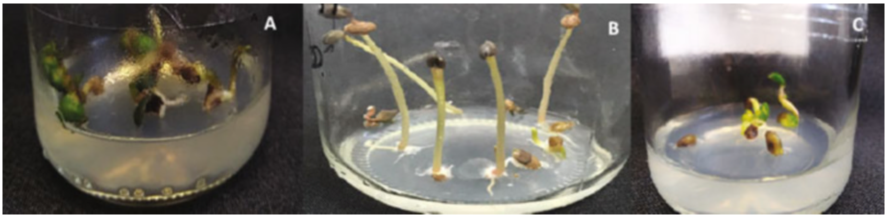

Fig. 12.5 Scarification methods of Lupinus seed with H_2SO_4, (**a**) *L. campestris*; (**b**) *L. bilineatus*; (**c**) *L. montanus*

micronutrients to crops like beans, rice (*Oryza sativa* L.), and wheat by using conventional plant breeding and biotechnology, making the basic food more nutritious, specifically in developing countries (Khush 2008). Children and women (because menstruation and childbirth) are the most vulnerable part of the population to the micronutrient deficiencies (Singh 2009). About half of the planet population suffers deficiencies of micronutrients such as Zn, Fe, and vitamins like vitamin A inducing to several symptoms related to impaired immune function, iron deficiency anemia, and xerophthalmia. The solution to this nutrition problem is to diversify the diet, but the poverty of these affected people makes it impossible; thus, biofortification of crops may take part in the solution (Jena et al. 2018). According to Bouis et al. (2017), some fortified foods include iodized salt, cooking oil, and sugar with added vitamin A, and iron biofortified flour, dairy foods, condiments, sugar, and salt.

12.4.2 Genetically Modified Organisms and Sustainability

The role of GMOs technology in the sustainable development of agriculture is yet debatable in many countries, mainly in topics like pests and diseases, drought, malnutrition, and food insecurity in developing countries (James 2014). According to Adenle et al. (2013), the GMOs technology, at that time, had not impacted notoriously on food security because of the debate about regulation of GMO products and also because of the disagreement surrounding the adoption of GMOs. The first genetically modified food authorized for human consumption was the Flavr Savr tomato in 1994. This tomato spoils more slowly than the conventional one, which allows farmers to collect the fruits when they are ripe, instead of before reaching maturity, unlike traditional tomatoes. However, it turned out to be a commercial failure (Weasel 2008). A tomato that can fight cancer because it contains three more times lycopene than conventional varieties was developed by Purdue University and the United States Department of Agriculture's Agricultural Research Service (Awais et al. 2010). Lycopene is a carotenoid pigment with antioxidant properties, and it can trap molecules that damage tissues in the human body, lowering the possibility of breast and prostate cancers.

Regardless of all the excellent results of biotechnology in agriculture, transgenic foods are still connected with a deficiency of information about their effects on the environment and human health (Boccia and Sarnacchiaro 2015).Altieri (2003) points out that although the declared end of plant biotechnology is the reduction of hunger, the planet generates enough food for it, and that the problem lies not in production, but the unequal distribution and the conversion of food production in agribusiness. One of the risk elements that most concern about GMOs is their effects on health, which have been widely speculated. Favorable or unfavorable positions can be assumed towards biotechnology, according to the optimistic or pessimistic views of those who do the analysis (Wilches 2010). However, there is already some research that points out the effects of transgenic products on health. Carman et al. (2013) studied the influence of transgenic foods in pigs that were fed with transgenic soybean and corn; the autopsy of the pigs showed stomach inflammations 2.6 times higher than those of pigs that ate conventional soybean and corn. Also, female pigs fed with the mixture of genetic modified (GM) soybean and corn had significantly higher uteri than those who ate non-GM soybean and corn. According to the authors, this could be associated with different types of pathologies, several of them malignant, a situation that deserves more detailed studies. A very alarming element is that humans and pigs have very similar anatomical characteristics, particularly in the digestive system, so that more in-depth studies in humans should be carried out before further enhancing the consumption of transgenic foods (Héctor et al. 2016).

Bøhn et al. (2014) showed that high concentrations of glyphosate and aminomethylphosphonic acid (AMPA) accumulate in Roundup Ready soybeans from Monsanto Corporation. This is the result of glyphosate herbicide applications, which are not present in conventional soybeans or organic soybeans, as this species is susceptible to that herbicide. Besides, significantly lower levels of protein were found in transgenic soybeans and considerably higher concentrations of fatty acids that can lead to obesity compared to conventional and organic soybeans. Other herbicide-tolerant crops are those carrying the gene *pat* derived from the common soil bacterium *Streptomyces viridochromogenes* for the herbicide glufosinate ammonium (PPT). This herbicide inhibits the enzyme glutamine synthetase, which causes abnormal accumulation of ammonia in plants, and the acetylated form of PPT is inactive (Oberdoerfer et al. 2005). There are several crops displaying resistance such as sugar beet (*Beta vulgaris*), canola (*Brassica* spp.), soy, rice, and corn (CERA 2010).

While the results of modern biotechnology are unquestionable in terms of solving the scientific problem that they intend to, it is also true that behind these advances, a powerful profit motive move. In 2008 (the landscape had not changed) ten large companies controlled more than 30% of world seed trade, and five companies (AstraZeneca, DuPont, Monsanto, Novartis, and Aventis) had the control of 60% of the world pesticide trade, plus 20% of the seed market and practically 100% of the transgenic seed trade (De la Torre 2008). Under these conditions, it is impossible to coincide with García-Gonzáles et al. (2010) when they state that access to technology is no longer exclusive to developed countries and that everyone needs to recognize its potential and exploit it in all its dimensions. It is not enough to want to do it; we need to be able to do it (Héctor et al. 2016). Farmers that start to reduce the application of chemicals try to use other ecological practices even when they do not practice yet all sustainable technologies (Hubbell and Welsh 1998).

12.4.3 Biotechnology and Sustainable Agriculture

Biotechnology works with living organisms, so many public opinion and debates have been developed in this matter. According to Singh (2000), biotechnology, biodiversity, and sustainable agriculture are complementary to each other, independent and free of contradictions even when topics like food security and biosafety can be in illogicality. Genetic engineering through horizontal gene transfer is part of this contradiction because it can be a threat to biodiversity and sustainability. The similarity between organisms gets to the dilution of smooth gene transfer risk (Singh 2000). The contribution of biotechnology to sustainable agriculture has been indifferent topics such as (Singh 2000):

- Resistance to biotic stresses has been increased (pest and diseases);
- Resistance to abiotic stresses has been improved (salinity, drought, cold);
- Solutions to soils contaminated with heavy metals (bioremediation, phytoremediation);
- Crops productivity and quality have grown;
- Fermentation technology has been improved;
- Nutrient uptake and efficient use have been increased, and nitrogen fixation has been enhanced; and some others.

In other words, biotechnology contributes to sustainable agriculture with the obtainment of crop resistance to pesticides which trends to reduce the dependence on agrochemicals; the production of crops would also achieve a reduction of chemicals fertilizers with better uptake and efficient use of nutrients; improvement of productivity and quality of crops increases market offers (Persley 2000). Biotechnology can include traditional and local knowledge, organic practices, tissue culture and genomic techniques; marker-assisted technology, transgenics, and others (Heinemann 2009). Causes of environmental degradation that biotechnology elude are poverty and socioeconomic differences. These causes also lead to political insecurity and social conflicts, resulting in more unsustainability. In the other hand, the actual tendency of biotechnology—development generally has been pro-rich and must of the results are applying in the private sector of developed countries—is not sustainable. The responsibility of promoting modern biotechnology in favor of poor people is in the hands of developing countries. Some of these contradictions respond to the fact that biotechnology stores high amounts of national resources for research and technology development at the cost of some of the conventional but vital programs (Singh 2000). Godfray et al. (2010a, b) mention the arguments that support using technology to boost yields are typically predicated on global models that project rising demand for food due to population growth and increasing affluence.

To transform countries that are not industrialized into industrialized ones, biotechnology techniques can offer support to guarantee sustainability and to decrease adverse environmental impacts that can occur. In agricultural business progress, for example, mediations might start from contributions and agricultural modernization, actual processing technologies, packing of delicate foods, the promotion of food safety in the processing and regulatory environment; and interventions to improve competitiveness and productivity (Lokko et al. 2018). Besides, in agriculture, the identification of species will require the sequence of the whole genome of each new species. Specifically, in entomology, the use of biotechnology is recommended to overcome the disadvantages of morphological identification, molecular techniques for insect identification have been adapted. Nowadays, most of the DNA extraction protocols of insect tissues are based on the manual methods of CTAB, phenol-chloroform, SDS/proteinase K, or commercial kits available (Calderón-Cortés et al. 2010; Shams et al. 2011).

For PCR, use should be made of RFLP (Qin et al. 2008), DNA barcode (Yang et al. 2012), species-specific primer (SS-PCR) (Zhao et al. 2016), multiplex endpoint PCR, and qPCR TaqMan multiplex (Arif et al. 2015), among others. Currently, some molecular markers such as the cytochrome c oxidase subunit I (IOC), the 16S ribosomal RNA gene (16S rDNA), the internal transcribed spacer 2 (ITS2) and microsatellites have proven effective in identifying insect species (Li et al. 2011).

In recent years, the microarray technique has begun to be used for the identification of insects. The sequencing of two mitochondrial genes (IOC and ND2) and the ribosomal gene (ITS2) have been used to design species-specific probes. In addition to the gene chip method developed in that same way, it has allowed the identification of species of genera important ones such as Aedes, Anopheles, Armigeres, and Culex (Wang et al. 2017b). The developing countries should widely apply the results of the biotechnology. In this matter plants free of diseases obtained by tissue culture are used by small farmers in these countries. Another example is papaya plants resistant to the virus that was developed in Hawaii, which are used in developing countries (Serageldin 1999). In the Democratic Republic of the Congo, tissue culture is used in food security, and cassava clones free of diseases are propagated in Nigeria (FAO 2001). In Kenya, free-disease banana plants, obtained through tissue culture, help in the increase of yield and to protect incomes of farmers threatened because of the loss of commercial coffee crops. In Uganda, as a result of cooperation between the International Potato Center in Peru and Ugandan National Agricultural Research Organization, potato plants free of diseases are introduced and growth. All these are examples that imply biotechnology helping the poor and the hungry (Wambugu 2001). Rural populations poverty is mainly because the water resources are not enough; the crops yield is low, which leads to the deficient food supply, food insecurity, damaged environment, and hunger (Serageldin 1999). Biotechnology in many countries means economic development and social progress (DaSilva 1998) giving access to technology by credits, especially to poor rural farmers (Holaday 1999).

12.5 Conclusions

Since before the first products appeared on the market, high expectations had been created on the potential of the new biotechnology as a vital tool in the supply of food to a continuously growing human population. Agricultural genetic engineering has been considered as the spearhead of a new revolution capable of improving productivity by reducing costs, helping in the adoption of more environmentally friendly agricultural practices, and serving as a development engine for developing countries. At present, both the use of traditional techniques and innovative techniques to achieve sustainable agriculture are considered. An efficient agroecological approach requires the effective implementation of new technologies, which can be adjusted in sustainable development programs, drawing various alternatives; the products obtained from biotechnology must serve to overcome different problems: diseases, pests, and environmental limitations of plant production.

12.6 Future Perspectives

Biotechnology is a tool that will continue to be used in agriculture due to its wide applications, many of which contribute to sustainability. Obtaining transgenic crops with all the necessary tests before releasing them to the market, can contribute to agricultural sustainability. These crops can resist high temperatures, frost, salinity, drought, pathogens (which implies the reduction in the application of pesticides), crops that require less chemical fertilizers, like pesticides that pollute the environment (soil, water, air). Tissue culture also opens paths in this matter because it is a technology that allows cloning plants with characteristics of resistance to the factors mentioned above. Also, biotechnology offers several gains for agricultural productivity that represent contributions to sustainability such as decreasing poverty and increasing food security in developing countries. Another technology that is already used, but is part of the future of agricultural sustainability is nanotechnology, which also helps to reduce contamination by applying chemicals for pest control and fertilizers at the nano level.

References

Abdelsalam A, Chowdhury K, El-Bakry A (2018) Efficient adventitious morphogenesis from *in vitro* cultures of the medicinal plant *Cymbopogon schoenanthus*. Plant Tissue Cult Biotechnol 28(2):147–160

Abraham A (2009) Agricultural biotechnology research and development in Ethiopia. Afr J Biotechnol 825(29):7196–7204

Abudayyeh OO, Gootenberg JS, Konermann S, Joung J, Slaymaker IM et al (2016) C2c2 is a single component programmable RNA-guided RNA-targeting CRISPR effector. Science 353:5573–5673

Abudayyeh OO, Gootenberg JS, Essletzbichler P, Han S, Joung J et al (2017) RNA targeting with CRISPR-Cas13. Nature 550:280–244

Adenle AA, Morris EJ, Govindan P (2013) Status of development, regulation and adoption of GM agriculture in Africa: Views and positions of stakeholder groups. Food Policy 42:159–166

Altieri MA (2003) Dimensiones éticas de la crítica agroecológica a la biotecnología agrícola. Acta Bioethica Año 9(1):47–61

Altieri MA, Nicholls CI (2017) Agroecology: a brief account of its origins and currents of thought in Latin America. Agroecol Sustain Food Syst 41(3-4):231–237

Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sustain Dev 32:1–13

Andersson M, Turesson H, Olsson N, Fält AS, Ohlsson P, Gonzalez-Matías N, Samuelsson M, Hofvander P (2018) Genome editing in potato via CRISPR-Cas9 ribonucleoprotein delivery. Physiol Plant 164:378–384

Arif M, Opit G, Mendoza-Yerbafria A, Dobhal S, Li Z, Kučerová Z, Ochoa-Corona FM (2015) Array of synthetic oligonucleotides to generate unique multi-target artificial positive controls and molecular probe-based discrimination of Liposcelis species. PLoS One 10(6):e0129810

Awais MA, Pervez A, Yaqub R, Sarwar F, Siraj S (2010) Current status of biotechnology in health. Am Eurasian J Agric Environ Sci 7(2):210–220

Bagwan JD, Patil SJ, Mane AS, Kadam VV, Vichare S (2010) Genetically modified crops: food of the future. Int J Adv Biotechnol Res 1(1):21–30

Bahadur S, Verma SK, Prasad SK, Madane AJ, Maurya SP, Gaurav VVK, Sihag SK (2015) Eco-friendly weed management for sustainable crop production-a review. J Crop Weed 11 (1):181–189

Baird V, Abbott A, Ballard R, Sosinski B, Rajapakse S (1997) DNA diagnostics in horticulture. In: Current topics in plant molecular biology: technology transfer of plant biotechnology. CRC Press, Boca Raton, pp 111–130

Balwinder SS, Singh GV, Kaur AN (2011) An efficient plant regeneration protocol from callus cultures of *Citrus jambhiri* Lush. Physiol Mol Biol Plants 17(2):161–169

Baranski R, Klimek-Chodacka M, Lukasiewicz A (2019) Approved genetically modified (GM) horticultural plants: A 25-year perspective. Folia Hortic 31(1):3–49

Barrangou R, Horvath P (2017) A decade of discovery: CRISPR functions and applications. Nat Microbiol 2:17092

Basu SK, Dutta M, Goyal A, Bhowmik PK, Kumar J, Nandy S, Scagliusi SM, Prasad R (2010) Is genetically modified crop the answer for the next green revolution? GM Crops 1(2):68–79

Bates SL, Zhao JZ, Roush RT, Shelton AM (2005) Insect resistance management in GM crops: past, present and future. Nat Biotechnol 23(1):57–62

Benor S, Zhang M, Wang Z, Zhang H (2008) Assessment of genetic variation in tomato (*Solanum lycopersicum* L.) inbred lines using SSR molecular markers. J Genet Genomics 35(6):373–379

Bestelmeyer BT, Okin GS, Duniway MC, Archer SR, Sayre NF, Williamson JC, Herrick JE (2015) Desertification, land use, and the transformation of global drylands. Front Ecol Environ 13 (1):28–36

Boccia F, Sarnacchiaro P (2015) Genetically modified foods and consumer perspective. Recent Pat Food Nutr Agric 7:28–34

Bogdanove AJ, Voytas DF (2011) TAL effectors: customizable proteins for DNA targeting. Science 333:1843–1846

Bøhn T, Cuhra M, Traavik T, Sanden M, Fagan J, Primicerio R (2014) Compositional differences in soybeans on the market: glyphosate accumulates in Roundup Ready GM soybeans. Food Chem 153:207–215

Botstein D, White RL, Skolnick M, Davis RW (1980) Construction of a genetic linkage mapping man using restriction fragment length polymorphisms. Am J Hum Genet 32:314–331

Bouis H, Saltzman A, Low J, Ball AM, Covic MN (2017) An overview of the landscape and approach for biofortification in Africa. Afr J Food Agric Nutr Dev 17:11848–11864

Brookes G, Barfoot P (2018) GM crops: global socio-economic and environmental impacts 1996–2006. PG Economics Ltd, Dorchester, p 204

Brundtland GH (1987) Our common future. Oxford University Press, Oxford, p 300

Burstein D, Harrington LB, Strutt SC, Probst AJ, Anantharaman K, Thomas BC, Doudna JA, Banfield JF (2017) New CRISPR-Cas systems from uncultivated microbes. Nature 542:237–241

Buttel FH (2003) Internalising the societal costs of agricultural production. Plant Physiol 133:1656–1665

Calderón-Cortés N, Quesada M, Cano-Camacho H, Zavala-Páramo G (2010) A simple and rapid method for DNA isolation from xylophagous insects. Int J Mol Sci 11(12):5056–5064

Carman JA, Vlieger HR, Ver Steeg LJ, Sneller VE, Robinson GW, Clinch-Jones CA, Haynes JI, Edwards JW (2013) A long-term toxicology study on pigs fed a combined genetically modified (GM) soy and GM maize diet. J Org Syst 8(1):38–54

Casierra F, Aguilar OE (2007) Estrés por aluminio en plantas: Reacciones en el suelo, síntomas en vegetales y posibilidades de corrección. Una revisión. Rev Colomb Cienc Hortic 1(2):246–257

CERA (2010) GM crop database. ILSI Research Foundation, Washington DC

Chandrasekaran J, Brumin M, Wolf D, Leibman D, Klap C, Pearlsman M, Sherman A, Arazi T, Gal-On A (2016) Development of broad virus resistance in non-transgenic cucumber using CRISPR/Cas9 technology. Mol Plant Pathol 17:1140–1153

Chen L, Li W, Katin-Grazzini L, Ding J, Gu X, Li Y, Gu T, Wang R, Lin X, Deng Z et al (2018) A method for the production and expedient screening of CRISPR/Cas9-mediated non-transgenic mutant plants. Hortic Res 5:13

Chiruvella KK, Mohammed A, Dampuri G, Gopal RG (2011) *In vitro* shoot regeneration and control of shoot tip necrosis in tissue cultures of *Soymida febrifuga* (Roxb.) A. Juss. Plant Tissue Cult Biotechnol 21(1):11–25

CINU (2011) Alimentación. CINU. http://www.cinu.org.mx/temas.htm

Conway GR, Barbier EB (1990) After the green revolution. Sustainable agriculture for development. Earthscan, London, p 210

Dalgaar T, Hutchings NJ, Porter JR (2003) Agroecology, scaling and interdisciplinarity. Agric Ecosyst Environ 100:39–51

Dash A, Kundu D, Das M, Bose D, Adak S, Banerjee R (2016) Food biotechnology: a step towards improving nutritional quality of food for Asian countries. Recent Pat Biotechnol 10:43–57

DaSilva EJ (1998) Biotechnology, developing countries and globalization. World J Microbiol Biotechnol 14:463–486

De la Torre J (2008) Aspectos éticos del uso de los organismos modificados genéticamente (OMG) en la agricultura y alimentación. ICADE 73:141–169

Dehmer KJ, Hammer K (2004) Taxonomic status and geographic provenance of germplasm accessions in the *Solanum nigrum* L. complex: AFLP Data. Genet Resour Crop Evol 51:551–558

Dhlamini Z, Spillane C, Moss JP, Ruane J, Urquia N, Sonnino A (2005) Status of research and application of crop biotechnologies in developing countries. Food and Agriculture Organization of the United Nations Natural Resources Management and Environment Department, Rome, p 65

Dixon GR, Tilson EL (2010) Soil microbiology and sustainable crop production. Springer, Dordrecht, p 435

Dobbs T, Pretty JN (2004) Agri-environmental stewardship schemes and multifunctionality. Rev Agric Econ 26:220–237

Dominguez MS, Jiménez LG, Rosales CG, Quiñones CV, Delgadillo SD, Mireles SJ, Pérez EM (2008) El cultivo in vitro como herramienta para el aprovechamiento, mejoramiento y conservación de especies del género Agave. Investig Cienc 41:53–62

Doudna JA, Charpentier E (2014) Genome editing. The new frontier of genome engineering with CRISPR-Cas9. Science 346:1258096

Dreger M, Mól R, Deja A, Raj E, Mańkowska G, Wielgus K (2019) Improved plant regeneration in callus cultures of *Sorghum bicolor* (L.) Moench. In Vitro Cell Dev Biol Plant 55:190–198

Du D, Jin R, Guo J, Zhang F (2019) Construction of marker-free genetically modified maize using a heat-inducible auto-excision vector. Gene 10(374):1–17

Dyllick T, Hockerts K (2002) Beyond the business case for corporate sustainability. Business Strat Environ 11(2):130–141

EA (2005) Assessment of win–win case studies of resource management in agriculture. Bristol, EA and English Nature, p 132

Eagles HA, Bariana HS, Ogbonnaya FC, Rebetzke GJ, Hollamby GJ, Henry RJ, Henschke PH, Mcneil MD (2001) Implementation of markers in Australian wheat breeding. Crop Pasture Sci 52(12):1349–1356

Espinoza EFM (2018) Biotecnología para la agricultura moderna. Ciencia 69(4):1–6

FAO (2001) Action against undernutrition and poverty. Redirecting food assistance to those who need it most. In: The state of food insecurity in the world. http://www.fao.org/docrep/003/y1500e/y1500e05.htm#P0_0

FAO (2011) Biotechnologies for agricultural development. FAO, Rome, p 569

FAO (2014a) The water-energy-food nexus: a new approach in support of food security and sustainable agriculture. FAO, Rome, p 28

FAO (2014b) Anuario Estadístico: La alimentación y la agricultura en América Latina y el Caribe. https://www.fao.org/3/a-i3592s.pdf

FAO (2017) El futuro de la alimentación y la agricultura: Tendencias y desafíos. p 52, www.fao.org/publications

FAO-FIDA-PMA (2014) El estado de la inseguridad alimentaria en el mundo 2014: fortalecimiento de un entorno favorable para la seguridad alimentaria y la nutrición. FAO, Roma, p 62

Farooq S, Iqbal N, Arif M (1996) Detection of genetic variability in basmati and non-basmati rice varieties and their radiation induced mutants through random amplified polymorphic DNA (RAPD). International Atomic Energy Agency, Vienna (Austria); Food and Agriculture Organization of the United Nations, Rome (Italy); Proceedings series, p 748

Figueroa-Rodríguez MI (2016) Efecto de especies nativas y silvestres del género Lupinus sobre la fertilidad del suelo agrícola. Maestría en Ciencias en Desarrollo de Productos Bióticos, CeProBi-IPN, México, p 107

Firbank LG, Rothery P, May MJ, Clark SJ, Scott RJ, Stuart RC, Boffey CWH, Brooks DR, Champion GT, Haughton AJ, Hawes C, Heard MS, Dewar AM, Perry JN, Squire GR (2006) Effects of genetically modified herbicide-tolerant cropping systems on weed seedbanks in two years of following crops. Biol Lett 2:140–143

Firbank LG, Petit S, Smart S, Blain A, Fuller RJ (2008) Assessing the impacts of agricultural intensification on biodiversity: a British perspective. Philos Trans R Soc B 363:777–787

Fornasini M, Castro J, Villacres E, Narvaez L, Villamar M, Baldeon ME (2012) Hypoglycemic effect of *Lupinus mutabilis* in healthy volunteers and subjects with dysglycemia. Nutr Hosp 27 (2):425–433

García-Gonzáles R, Quiroz K, Carrasco B, Caligari P (2010) Plant tissue culture: current status, opportunities and challenges. Cien Investig Agrar 37(3):5–30

Gätjens-Boniche O, Acuña-Matamoros CL, Montero-Carmona W, Díaz C, Torres S (2018) Vanilla mass propagation and protocormic callus formation from root tips. PoliBotánica 45:157–180

Gerszberg A, Grzegorczyk-Karolak I (2019) Influence of selected antibiotics on the tomato regeneration in *in vitro* cultures. Notulae Bot Hortic Agrobot Cluj-Napoca 47(3):558–564

Gliessman SR (2005) Agroecology and agroecosystems. In: Pretty J (ed) The Earthscan reader in sustainable agriculture. Earthscan, London

Gliessman SR (2013) Agroecología: plantando las raíces de la resistencia. Agroecología 8(2):19–26

Godfray H, Charles J, Beddington JR, Crute IR, Haddad L, Lawrence D et al (2010a) Food security: the challenge of feeding 9 billion people. Science 327(5967):812–818

Godfray H, Charles J, Crute IR, Haddad L, Lawrence D, Muir JF et al (2010b) The future of the global food system. Philos Trans R Soc B Biol Sci 365(1554):2769–2777

Gregory PJ, Johnson SN, Newton AC, Ingram JSI (2009) Integrating pests and pathogens into the climate change/ food security debate. J Exp Bot 60:2827–2838

Gupta PK, Durzan DJ (1985) Shoot multiplication from mature trees of Douglas-fir and sugar pine. Plant Cell Rep 4:177–179

Gustavsson J, Cederberg C, Sonesson U (2011) Global food losses and food waste. Food and Agriculture Organization of the United Nations, Rome

Gutiérrez DF, Ruiz RM, Xoconostle BC (2015) Estado actual de los cultivos genéticamente modificados en México y su contexto internacional. Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, México, p 194

Haberl H, Schulz NB, Plutzar C, Erb HK, Krausmann F, Loib W, Moser D, Sauberer N, Weisz H, Zechmeister G, Zulka P (2004) Human appropriation of net primary production and species diversity in agricultural landscapes. Agric Ecosyst Environ 102:213–218

Habets M, van Hove L, van Est R (2019) Genome editing in plants and crops – Towards a modern biotechnology policy focused on differences in risks and broader considerations. Rathenau Institute, The Hague, p 48

Hammschlag F, Ritchie D, Werner D, Hashmil G, Krusberg L, Meyer R, Huettel R (1995) *In vitro* selection of disease resistance in fruit trees. Acta Hortic 392:19–26

Hancock JM (1999) Microsatellites and other simple sequences: genomic context and mutational mechanisms. In: Goldstein DB, Schlötterer C (eds) Microsatellites, evolution and applications. Oxford University Press, Oxford, pp 1–10

Hans BV, Colaco VM (2019) Sustainable agriculture and economic growth. JETIR 6(1):483–512

Héctor E, Pérez-Álvarez S, Moreira R, Millet B (2016) Perspectivas futuras e impacto social de las biotecnologías vegetales. Alternativas 17(2):44–51

Héctor E, Millet B, Torres A, Fosado O (2018) Agricultura en Sudamérica: La huella ecológica y el futuro de la producción agrícola. Rev Chakiñan 5:90–101

Heinemann J (2009) Hope not hype: The future of agriculture guided by the international assessment of agricultural knowledge, science and technology for development. Third World Network, Penang

Henry RJ (1997) Practical applications of plant molecular biology. Chapman & Hall, London, p 280

Henry RJ (2001) Plant genotyping: the DNA fingerprinting of plants. CABI Publishing, Oxford, pp 239–249

Holaday JW (1999) Competing in the new millennium: challenges facing small biotechnology firms. Congressional Testimony -Subcommittee on Technology, 27 October, 1999. http:www.house.gov/science/holaday-102799.htm

Huang J, Tichit M, Poulot M, Darly S, Li S, Petit C, Aubry C (2015) Comparative review of multifunctionality and ecosystem services in sustainable agriculture. J Environ Manag 149:138–147

Hubbell B, Welsh R (1998) Transgenic crops: engineering a more sustainable agriculture? Agric Hum Values 15:43–56

Iriawati PMR, Rodiansyah A (2017) *In vitro* regeneration of foxtail millet (*Setaria italica* (L.) Beauv.) cv. Buru Hotong. J Math Fund Sci 49(2):171–180

ISAAA (2016) Global status of commercialized biotech/ GM crops: ISAAA brief 52. ISAAA, Ithaca

Islam MM, Ahmed M, Mahaldar D (2005) *In vitro* callus induction and plant regeneration in seed explants of rice (*Oryza sativa* L.). Res J Agric Biol Sci 1:72–75

James C (2014) Global status of commercialized biotech/GM crops: 2014, executive summary. Dedicated to the late Nobel Peace Laureate, Norman Borlaug, (ISAAA Brief 49), p. 32 http://www.isaaa.org/resources/publications/briefs/49/executivesummary/default.asp and top ten facts: http://www.isaaa.org/resources/publications/briefs/49/toptenfacts/default.asp and http://www.askforce

Jena J, Sethy P, Jena T, Ranjan SM, Kumar SS, Kumar GD, Palai JB (2018) Rice biofortification: a brief review. J Pharmacogn Phytochem 7(1):2644–2647

Jiang GL (2013) Molecular markers and marker-assisted breeding in plants. In: Andersen SB (ed) Plant breeding from laboratories to fields. InTech, Rijeka, pp 45–83

Keong C, Nordin FA, Bhatt A, Keng C (2018) Culture medium and varietal selection for establishment of callus culture of *Artemisia annua*. Educ JSMT 5(2):67–76

Khush GS (2008) Biofortification of crops for reducing malnutrition. Proc Indian Natl Sci Acad 74 (1):21–25

Koonin EV, Makarova KS, Zhang F (2017) Diversity, classification and evolution of CRISPR-Cas systems. Curr Opin Microbiol 37:67–78

Kumar V, Sharma S, Kero S, Sharma S, Sharma AK, Kumar M, Bhat KV (2008) Assessment of genetic diversity in common bean (*Phaseolus vulgaris* L) germplasm using amplified fragment length polymorphism (AFLP). Sci Hortic 116:138–143

Kumar S, Kakraliya SK, Lakhran H, Sheoran S, Ram M, Meena RS (2016a) Use of *Bacillus thuringiensis* (Bt) Gene: a biotechnological tool for crop improvement. Prog Res 11:6247–6251

Kumar S, Sheoran S, Kakraliya SK, Kumar P, Meena RS (2016b) Drought: A challenge for Indian farmers in context to climate change and variability. Prog Res 11:6243–6246

Kumar S, Meena RS, Jakhar SR, Jangir CK, Gupta A, Meena BL (2019) Adaptation strategies for enhancing agricultural and environmental sustainability under current climate. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jaipur, pp 226–274

Langner T, Kamoun S, Belhaj K (2018) CRISPR crops: Plant genome editing toward disease resistance. Annu Rev Phytopathol 56:22.1–22.34

Levitus G, Echenique V, Rubinstein C, Hoop E, Mroginski L (2010) Biotecnología y mejoramiento vegetal II. ArgenBio. Consejo Argentino para la Información y el Desarrollo de la Biotecnología, Argentina, p 650

Li ZH, Kučerová Z, Zhao S, Stejskal V, Opit G, Qin M (2011) Morphological and molecular identification of three geographical populations of the storage pest *Liposcelis bostrychophila* (Psocoptera). J Stored Prod Res 47(3):168–172

Lokko Y, Heijde M, Schebesta K, Scholtés P, Van Montagu M, Giacca M (2018) Biotechnology and the bioeconomy-Towards inclusive and sustainable industrial development. New Biotechnol 40:5–10

López-Jaimes EL (2014) Diversidad de bacterias asociadas a la rizosfera de *Lupinus montanus* Kunth. Tesís de Maestría en Ciencias. Instituto Politécnico Nacional, Morelos

Maeder ML, Thibodeau-Beganny S, Osiak A, Wright DA, Anthony RM (2008) Rapid "opensource" engineering of customized zinc-finger nucleases for highly efficient gene modification. Mol Cell 31:294–301

Malabadi RB, Choudhury H, Tandon P (2004) Initiation, maintenance and maturation of somatic embryos from thin apical dome sections in *Pinus kesiya* (Royle ex. Gord) promoted by partial desiccation and Gellan gum. Sci Hortic 102:449–459

Malabadi RB, Mulgund GS, Nataraja K (2005) Plant re generation via somatic embryogenesis in *Pinus kesiya* (Royle ex. Gord.) influenced by triacontanol. Acta Physiol Plant 27(4A):531–537

Malabadi RB, Teixeira da Silva JA, Nataraja K, Vijaykumar S, Mulgund SG (2011a) Induction of somatic embryogenesis in mango (*Mangifera indica* L.). Int J Biol Technol 2(2):12–18

Malabadi RB, Vijaya SK, Mulgund GS, Nataraja K (2011b) Induction of somatic embryogenesis in Papaya (*Carica papaya*). Res Biotechnol 2(5):40–55

McNeely JA, Scherr SJ (2003) Ecoagriculture. Island Press, Washington, DC, p 319

MEA (2005) Ecosystems and human well-being. Island Press, Washington, DC, p 155

Meena RS, Kumar V, Yadav GS, Mitran T (2018) Response and interaction of Bradyrhizobium japonicum and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Kumar S, Bohra JS, Lal R, Yadav GS, Pandey A (2019) Response of alley cropping-grown sesame to lime and sulphur on yield and available nutrient status in an acidic soil of Eastern India. Energy Ecol Environ 4:65–74

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Méndez-López A, Villanueva-Verduzco C, Rojas-Martínez RI, Sahagún-Castellanos J, Colinas-León MT, Sánchez-Vega M (2019) Genetic diversity of parthenocarpic genotypes shrubby squash using molecular genetic markers. Rev Mex Cienc Agríc 10(1):1–9

Mitsunobu H, Teramoto J, Nishida K, Kondo A (2017) Beyond native Cas9: manipulating genomic information and function. Trends Biotechnol 35:983–996

Mohamed FH, Omar GF, Ismail MA (2017) *In vitro* regeneration, proliferation and growth of strawberry under different light treatments. Acta Hortic 1155:361–368

Mohler V, Schwarz G (2005) Genotyping tools in plant breeding: From restriction fragment length polymorphisms to single nucleotide polymorphisms. In: Molecular marker systems in plant breeding and crop improvement. Springer, Cham, pp 23–38

Mor-Mussery A, Leu S, Budovsky A, Lensky I (2015) Plant-soil interactions and desertification: a case study in the Northern Negev, Israel. Arid Land Res Manag 29(1):85–97

Mullis KB (1990) The unusual origin of the polymerase chain reaction. Sci Am 262(4):56–61

Murashige T, Skoog F (1962) A revised medium for rapid growth and bioassays with tobacco tissue cultures. Physiol Plant 15:473–497

Ni J, Colowit PM, Mackill DJ (2002) Evaluation of genetic diversity in rice subspecies using microsatellite markers. Crop Sci 42(2):601–607

Nogue PY, Alberti A, Weissenbach J, Salanoubat M, Tolonen AC (2014) Functional diversity of carbohydrate-active enzymes enabling a bacterium to ferment plant biomass. PLoS Genet 10 (11):1–12

Norton BG (1995) Evaluating ecosystem states: two competing paradigms. Ecol Econ 14:113–127

Oberdoerfer RB, Shillito RD, De Beuckeleer M, Mitten DH (2005) Rice (*Oryza sativa* L.) containing the bar gene is compositionally equivalent to the nontransgenic counterpart. J Agric Food Chem 53:1457–1465

Olsson P, Folke P (2001) Local ecological knowledge and institutional dynamics for ecosystem management: a study of Lake Racken watershed, Sweden. Ecosystems 4:85–104

Ostrom E (1990) Governing the commons: the evolution of institutions for collective action. Cambridge University Press, New York, p 298

Padgette SR, Re DB, Barry GF, Eichholtz DE, Delannay X, Fuchs RL et al (1996) New weed control opportunities: development of soybeans with a Roundup Ready™ gene. Herbicide Resist Crops 2009:53–84

Paques F, Duchateau P (2007) Meganucleases and DNA double-strand break-induced recombination: perspectives for gene therapy. Curr Gene Ther 7:49–66

Parfitt J, Barthel M, Macnaughton S (2010) Food waste within food supply chains: quantification and potential for change to 2050. Philos Trans R Soc B 365:3065–3081

Paterson AH (1996) Making genetic maps. In: Paterson AH (ed) Genome mapping in plants. R G Landes Company, Austin, pp 23–39

Peng A, Chen S, Lei T, Xu L, He Y, Wu L, Yao L, Zou X (2017) Engineering canker-resistant plants through CRISPR/Cas9-targeted editing of the susceptibility gene CsLOB1 promoter in citrus. Plant Biotechnol J 15:1509–1519

Persley GJ (2000) Agricultural biotechnology and the poor: promethean science. In: Persley GJ, Lantin MM (eds) Agricultural biotechnology and the poor: Proceedings of an international conference Washington DC, 21-22 October 1999. Washington, Consultative Group on International Agricultural Research, pp 1–12

Pierik RLM (1987) *In vitro* culture of higher plants. Springer, Dordrecht, p 348

Pretty J (2003) Social capital and the collective management of resources. Science 302:1912–1915

Pretty J (2008) Agricultural sustainability: concepts, principles and evidence. Philos Trans R Soc B 363:447–465

Pretty J, Ward H (2001) Social capital and the environment. World Dev 29:209–227

Pretty JN, Toulmin C, Williams S (2011) Sustainable intensification in African agriculture. Int J Agric Sustain 9(1):5–24

Puchta H, Fauser F (2014) Synthetic nucleases for genome engineering in plants: prospects for a bright future. Plant J 78:727–741

Qaim M (2009) The economics of genetically modified crops. Ann Rev Resour Econ 1:665–694

Qin M, Li ZH, Kucerova Z, Cao Y, Stejskal V (2008) Rapid discrimination of the common species of the stored product pest Liposcelis (Psocoptera: Liposcelididae) from China and the Czech Republic, based on PCR-RFLP analysis. Eur J Entomol 105(4):713

Raintree JB, Warner K (1986) Agroforestry pathways for the intensification of shifting cultivation. Agrofor Syst 4:39–54

Ramírez-Contreras A, Rodríguez-Trejo DA (2009) Plantas nodriza en la reforestación con *Pinus hartwegii* Lindl. Revista Chapingo. Ser Cienc Forest Ambiente 15(1):43–48

Ramirez-Mozqueda MA, Iglesias Andreu LG (2017) Vanilla (*Vanilla planifolia* Jacks.) cell suspension cultures: establishment, characterization, and applications. Biotechnology 7 (4):242–248

Rao NK (2004) Plant genetic resources: Advancing conservation and use through biotechnology. Afr J Biotechnol 3(2):136–145

Reichert JM, Carneiro TJ, Reinert DJ, Rodrigues MF, Sanchez LEA (2016) Land use effects on subtropical, sandy soil under sandyzation/desertification processes. Agric Ecosyst Environ 233:370–380

Rodríguez DA, Rojo C (1997) Estudio de la semilla del arbusto *Lupinus montanus* H.B.K. (Leguminosae). Rev Chapingo Ser Cienc Forest 3:39–45

Ronald P (2008) The new organic. The Boston Globe, March 16. Available at http://www.boston.com/bostonglobe

Ronald P, Adamchak R (2008) Tomorrow's table: Organic farming, genetics, and the future of food. Oxford University Press, New York, p 228

Royal Society (2009) Reaping the benefits: science and the sustainable intensification of global agriculture. The Royal Society, London, p 86

Sarasan V, Cripps R, Ramsay MM, Atherton C, McMichen M, Prendergast G, Rowntree JK (2006) Conservation in vitro of threatened plants-progress in the past decade. In Vitro Cell Dev Biol Plant 42:206–214

Sax K (1923) The association of size differences with seed-coat pattern and pigmentation in *Phaseolus vulgaris*. Genetics 8:552–560

Schlötterer C (2000) Evolutionary dynamics of microsatellite DNA. Chromosoma 109:365–371

Scientific American (2009) Biotech's plans to sustain agriculture. Sci Am 301(4):86–94

Serageldin I (1999) Biotechnology and food security in the 21st century. Science 285:387–389

Shams SS, Vahed SZ, Soltanzad F, Kafil V, Barzegari A, Atashpaz S, Barar J (2011) Highly effective DNA extraction method from fresh, frozen, dried and clotted blood samples. Bioimpacts 1(3):183

Shetty MJ, Chandan K, Krishna HC, Aparna GS (2018) Genetically modified crops: an overview. J Pharmacogn Phytochem 7(1):2405–2410

Shure M, Wessler S, Fedoro N (1983) Molecular identification and isolation of the Waxy locus in maize. Cell 35:225–233

Singh RB (2000) Biotechnology, biodiversity, and sustainable agriculture: a contradiction. http://www.bic.searca.org/seminar_proceedings/Bangkok/2000/Hplenary_papers/singh.pdf

Singh MV (2009) Effect of trace element deficiencies in soil on human and animal health. Bull Indian Soc Soil Sci 27:75–101

Smith P (2013) Delivering food security without increasing pressure on land. Glob Food Secur 2:18–23

Smith J, Grizot S, Arnould S, Duclert A, Epinat JC, Chames P, Prieto J, Redondo P, Blanco FJ, Bravo J, Montoya G, Pâques F, Duchateau P (2006) A combinatorial approach to create artificial homing endonucleases cleaving chosen sequences. Nucleic Acids Res 34:e149

Steinert J, Schiml S, Fauser F, Puchta H (2015) Highly efficient heritable plant genome engineering using Cas9 orthologues from *Streptococcus thermophilus* and *Staphylococcus aureus*. Plant J 84:1295–1305

Stella S, Alcon P, Montoya G (2017) Class 2 CRISPR-Cas RNA-guided endonucleases: Swiss Army knives of genome editing. Nat Struct Mol Biol 24:882–892

Stepkowski T, Zak M, Moulin L, Króliczak J, Golińska B, Narożna D, Safronova V, Mądrzak CJ (2011) *Bradyrhizobium canariense* and *Bradyrhizobium japonicum* are the two dominant Rhizobium species in root nodules of lupin and serradella plants growing in Europe. Syst Appl Microbiol 34(5):368–375

Sturtevant AH (1913) The linear arrangement of six sex-linked factors in Drosophila, as shown by their mode of association. J Exp Zool 14:43–59

Swift MJ, Izac AMN, van Noordwijk M (2004) Biodiversity and ecosystem services in agricultural landscapes-are we asking the right questions? Agric Ecosyst Environ 104:113–134

Tapia ME, Fries AM (2007) Guía de Campo de los cultivos andinos. FAO-ANPE, Lima

Tegtmeier EM, Duffy MD (2004) External costs of agricultural production in the United States. Int J Agric Sustain 2:1–20

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci U S A 108:20260–20264

Tisserat B, Esan E, Murashige T (1979) Somatic embryogenesis in angiosperms. Hortic Rev 1:1–78

Touchell D, Smith J, Ranney TG (2008) Novel applications of plant tissue culture. Comb Proc Int Plant Propagat Soc 58:196–199

United Nations Environment Programme (2002) State of the environment and policy retrospective: 1972–2002. In: United Nations Environment Programme (ed) Global environment outlook 3. United Nations, New York, pp 1–30

Velten S, Leventon J, Jager N, Newig J (2015) What is sustainable agriculture? A systematic review. Sustainability 7:7833–7865

Voytas DF (2013) Plant genome engineering with sequence-specific nucleases. Annu Rev Plant Biol 64:327–350

Waltz E (2015) USDA approves next-generation GM potato. Nat Biotechnol 33:12–13

Wambugu F (2001) Modifying Africa: how biotechnology can benefit the poor and hungry, a case study from Kenya. In: Action against undernutrition and poverty, Nairobi, Kenya, p 76

Wang Y, Cheng X, Shan Q, Zhang Y, Liu J, Gao C, Qiu J-L (2014) Simultaneous editing of three homoeoalleles in hexaploid bread wheat confers heritable resistance to powdery mildew. Nat Biotechnol 32:947–951

Wang M, Mao Y, Lu Y, Tao X, Zhu JK (2017a) Multiplex gene editing in rice using the CRISPR-Cpf1 system. Mol Plant 10:1011–1013

Wang X, Tu WC, Huang EJ, Chen YH, Chen JH, Yeh WB (2017b) Identification of disease-transmitting mosquitoes: Development of species-specific probes for DNA Chip Assay using mitochondrial COI and ND2 genes and ribosomal internal transcribed spacer 2. J Med Entomol 54(2):396–402

Weasel LH (2008) Food fray: inside the controversy over genetically modified food. AMACOM, New York, p 258

Weeden N, Timmerman G, Lu J (1994) Identifying and mapping genes of economic significance. Expanding the production and use of cool season food legumes. Curr Plant Sci Biotechnol Agric 19:726–737

Wilches AM (2010) La biotecnología en un mundo globalizado. Rev Colomb Bioet 5(2):164–169

Williams JGK, Kubelik AR, Livak KJ, Rafalski JA, Tingey SV (1990) DNA polymorphisms amplified by arbitrary primers are useful as genetic markers. Nucleic Acids Res 18:6531–6535

Winter P, Kahl G (1995) Molecular marker technologies for plant improvement. World J Microbiol Biotechnol 11(4):438–448

Yadav GS, Lal, R, Meena RS (2020) Vehicular traffic effects on hydraulic properties of a Crosby silt loam under a long-term no-till farming in Central Ohio, USA. Soil Till Res. https://doi.org/10.1016/j.still.2020.104654

Yang Q, Kučerová Z, Li Z, Kalinović I, Stejskal V, Opit G, Cao Y (2012) Diagnosis of Liposcelis entomophila (Insecta: Psocodea: Liposcelididae) based on morphological characteristics and DNA barcodes. J Stored Prod Res 48:120–125

Yeung E, Rahman H, Thorpe T (1996) Comparative development of zygotic and microspore-derived embryos in *Brassica napus* L. cv Topas. I. Histodifferentiation. Int J Plant Sci 157 (1):27–39

Yildiz M (2012) The prerequisite of the success in plant tissue culture: High frequency shoot regeneration. In: Recent advances in plant *in vitro* culture. IntechOpen, Budapest, pp 63–90

Zane L, Bargelloni L, Patarnello T (2002) Strategies for microsatellite isolation: a review. Mol Ecol 11:1–16

Zhao ZH, Cui BY, Li ZH, Jiang F, Yang QQ, Kučerová Z, Li FJ (2016) The establishment of species-specific primers for the molecular identification of ten stored-product psocids based on ITS2 rDNA. Sci Rep 6:21022

Soil and Water Conservation Measures for Mediterranean Fruit Crops in Rainfed Hillslopes

13

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Abstract

Land degradation, singularly water erosion, is presently the main challenge for the agriculture of the Mediterranean basin. The combination of increasingly frequent extreme rainfall events and conventional farming practices coupled with steep slopes, poor soil structure and pauper plant cover are the elements that explain the development of water-driven soil erosion. The rainfed fruit crops with conventional practices register soil erosion values much higher than soil formation rates, affecting crop productivity. That is, runoff and soil losses are especially important in arid and semi-arid areas of the Mediterranean zones, where both these natural resources are the limiting factors for successful development and productivity of agroecosystems. Moreover, the forecasts for this region anticipate a more significant water shortage in the coming years with a possible severe impact on crop production. In this context, the use of soil and water conservation systems at wider scale are needed to reduce erosion and runoff, to increase the availability of water and plant nutrients, to avoid soil degradation and improve soil productivity. Because these are critical aspects for the economic and environmental sustainability of agricultural systems, especially in hilly areas. This chapter presents and discusses the advantages of conservation agriculture against conventional practices in rainfed fruit crops in terms of soil and water conservation.

Keywords

Agricultural runoff · Conservation agriculture · Mediterranean basin · Rainfed fruit crop · Soil degradation · Soil erosion

Abbreviations

CA	Conservation agriculture
EU	European Union
FAO	Food and Agriculture Organization
GAEC	Good agricultural and environmental conditions
Ha	Hectare
Kg	Kilogram
Mg	Milligram
MJ	Megajoule
Mm	Millimetre
SOC	Soil organic carbon
SOM	Soil organic matter
SWC	Soil and water conservation
T	Ton
UN	United Nations

13.1 Introduction

Soil is a non-renewable resource, and it is not recoverable, especially those devoted to agricultural activities, whose preservation is essential for sustainability (Lal 2008; Durán Zuazo et al. 2011). Soils produce food, feed, biomass and raw materials, and they are the habitat for organisms and genetic pool, act as carbon sinks, regulate geochemical cycles and water management (Fig. 13.1). This importance has led to both the United Nations (UN) and the European Union (EU) setting soil protection as a priority factor in their environmental policies. Thus, many of the UN Sustainable Development Goals have an active link with the sustainable management of water and soil (Keesstra et al. 2016a), and European Commission has developed a thematic strategy on soil protection.

The accelerated loss of the surface layer of the soil due to water erosion has long been recognized as one of the main threats to the world's soil resource. According to Pimentel and Burgess (2013), the rate of soil loss in agricultural areas is 10 to 40 times higher than its formation rate, which is a significant threat to food security. It is critical in areas like the Mediterranean mountain regions, where conventional agriculture records erosion rates that far exceed the rates of soil formation. It means that we can consider the soil as a non-renewable resource (FAO-ITPS 2015). In this sense, Panagos et al. (2015a) estimated an average soil loss due to water erosion in the EU of 2.46 t ha^{-1} year^{-1}, using the Revised Universal Soil Loss Equation (RUSLE 2015).

In Europe, Verheijen et al. (2009) establish a soil formation rate (1.4 t ha^{-1} year^{-1}) much lower than that of the average rate of soil loss. Also, must be taken into account that the model only estimates laminar and rill erosion, and does not take into account gully erosion; therefore, the risk of erosion is probably underestimated. In the EU there is a wide variety of erosion rates, due to the diversity in topography, climate and land use and management. Approximately, 11.4% of EU's territory is estimated

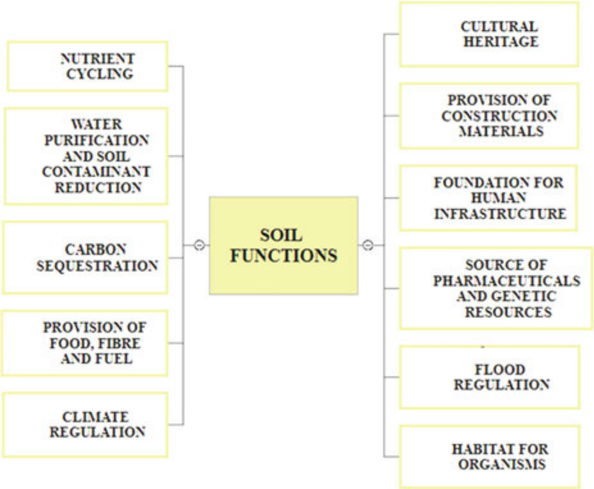


Fig. 13.1 Ecosystem services provided by the soil

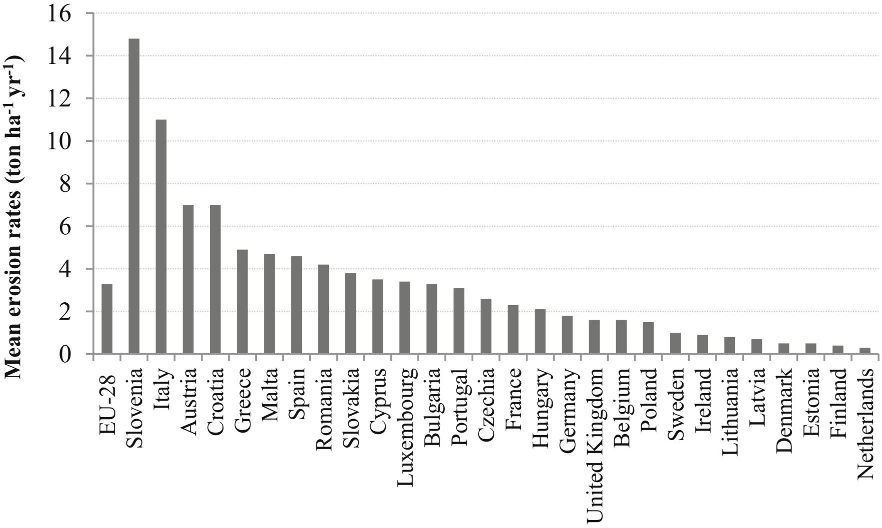


Fig. 13.2 Soil water erosion rates by country EU-28, 2016 (EUROSTAT 2020)

to be affected by a moderate to high-level soil erosion (EUROSTAT 2018). Roughly 67% of the total soil loss in the EU-28 is due to the contribution of eight member states of the Mediterranean region (Fig. 13.2) (Panagos et al. 2015a).

In the Mediterranean, soil erosion has been a historical environmental problem. That is, the unpredictable characteristics of the Mediterranean climate with scarce rainfalls, severe droughts and even high-intensity storms coupled with steep slopes make the favourable conditions for water erosion development (García-Ruiz et al. 2013). This problem is compounded by the use of practices such as intensive tillage and overgrazing.

Erosion problems are especially serious in fruit tree crops with conventional soil management. According to Maetens et al. (2012a), vineyards and fruit tree crops containing bare soil have the highest mean annual runoff coefficient (5–10%) and soil loss (10–20 Mg ha^{-1} $year^{-1}$) of uses of land in Europe and the Mediterranean.

On the other hand, the temporal and spatial variability of rainfall is one of the distinctive features of the Mediterranean climate. Extreme rainfall events of high intensity that generate significant rates of erosion and runoff are not rare in this type of environment (Martínez-Casasnovas et al. 2002). Important precipitation events are frequent in autumn and episodes of >200 mm in 1 day have been registered (Martínez Ibarra 2012; Valdes-Abellan et al. 2017). One or two events per year are usual which generates the highest percentage of annual soil losses (Ramos 2016). According to González Hidalgo et al. (2007), more than 50% of the annual soil loss is only due to the three highest erosive events. Climate forecasts for the Mediterranean region establish, among other effects of climate change, a significant reduction in net precipitation, more considerable interannual variability and augmentation of extreme events frequency (Goubanova and Li 2007; Giorgi and Lionello 2008). It could decrease available water in ecosystems, already having limited availability, and sensitive to desertification, such as the semi-arid areas of the Mediterranean region. This possible increase in water scarcity coupled with possible extreme weather events in southern Europe could decrease crop yields, could cause significant variability in production and a reduction in cultivable areas under traditional crops (Olesen and Bindi 2002). In the same line, Bakker et al. (2007) also predicated the significant decrease in crop productivity because of the soil erosion in southern Europe. According to Panagos et al. (2018), in EU the agricultural productivity loss due to soil erosion is 0.43% per year, accounting an economic loss of about € 1.25 million year^{-1}.

Besides having a high risk of erosive events, Mediterranean regions are also in danger of suffering flood damage or drought events (Panagos et al. 2015b). Vicente-Serrano et al. (2017) concluded that climate trends in Spain, compared to the last decades, showed drier and warmer conditions. This coincides with other studies for the Mediterranean area that showed a trend towards lower water availability (García-Ruiz et al. 2011) and more severe and frequent drought events (Hoerling et al. 2012). Soil erosion has significant environmental impacts whose repair involves high economic costs. Therefore, the use of soil and water conservation strategies (SWC) is essential to guarantee the economic and environmental sustainability of agricultural systems.

13.2 Need for Soil and Water Conservation

Land degradation is an environmental issue that affects natural and agricultural ecosystems around the world and negatively affects the well-being of approximately 3.2 billion people representing an economic loss of ~10% of the annual gross world product (IPBES 2018). More than 29% of the land area and 25% of farmland worldwide are affected by land degradation (Le et al. 2016). Soil erosion being the main cause of land degradation, though, is a natural process in the soil and landscape formation and evolution are greatly accelerated by certain human activities like for removal of vegetation cover, tillage, overgrazing, etc. (Borrelli et al. 2017). The accelerated erosion causes erosion rates that exceeding soil natural formation rates.

Soil erosion generates a series of adverse effects such as the decrease in the water storage capacity, the reduction of soil profundity, organic matter and the impact on the soil nutrient cycle due to changes in soil biodiversity as shown in Fig. 13.3. Besides, soil erosion negatively affects agricultural production by deteriorating the quality of water and environment in general; since it not only produces a series of adverse effects on the site but also generates others outside. In farmland, soil erosion reduces the infiltration capacity of water, moisture availability, drainage capacity, plant rooting depth and loss of soil nutrients. The fact that they are interconnected factors makes it difficult to elucidate how each of them individually influences the loss of soil productivity (Pimentel 2006). On the other hand, soil particles get displaced by erosion resulting in sedimentation and contamination of surface waters, blockage of waterways and destruction of infrastructure (Lal 2014). About 10 million

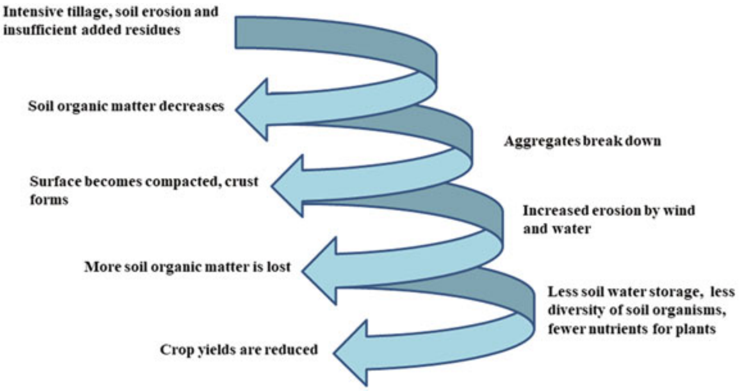


Fig. 13.3 The most common route of soil degradation

ha of cropland are abandoned annually worldwide due to the loss of productivity caused by soil erosion. In European agricultural areas it is estimated that every year erosion costs an average of 48 € ha^{-1}, of which 90% corresponds to the percentage represented by off-site damage (Montanarella 2007).

In European woody fruit crops, such as olive (*Olea europaea* L.), the vine (*Vitis vinifera* L.), almond (*Prunus dulcis* Mill.) and citrus fruits (*Citrus* sp.), there is a tendency to decrease of productivity as a result of land degradation, being 12% between 1982 and 2010 according to Cherlet et al. (2013). Soil and water losses are especially imperative in certain regions of the Mediterranean basin with water scarcity (Vanmaercke et al. 2011). According to Lagacherie et al. (2018), several attributes of the Mediterranean region explain the importance of soil erosion: (1) the relief with 45% of the areas having slopes more than 8%, (2) the high frequency of very intense rain events, (3) the limited protection against erosion exerted by vegetation, since coverage is scarce and (4) the low content of soil organic matter (SOM) that weakens the soil structure and is very susceptible to the action of raindrops. On the other hand, the most limiting natural resource in arid and semi-arid agroecosystems is water. In this line, traditional agronomic practices in the Mediterranean region for rainfed fruit crops have focused on increasing water availability to ensure their productivity and survival under water-limiting conditions. This has been achieved traditionally by combining three elements: (1) thick planting frames, (2) pruning to limit the size of the canopy and (3) removing weeds to prevent water loss. These practices leave a high percentage of bare soil, which causes accelerated soil loss (Fig. 13.4), decreased water quality due to off-site pollution and decreased biodiversity (Gómez 2017; Orgiazzi and Panagos 2018).

Olive groves and almond trees have traditionally been cultivated on marginal lands with poor agricultural aptitude, on sloping, rocky or shallow soils, and therefore susceptible to erosion. When these crops are abandoned, vegetation recovery is by far slow in the Mediterranean region (Rodrigo-Comino et al. 2018a). These are soils with limiting physical properties and very affected by erosive processes

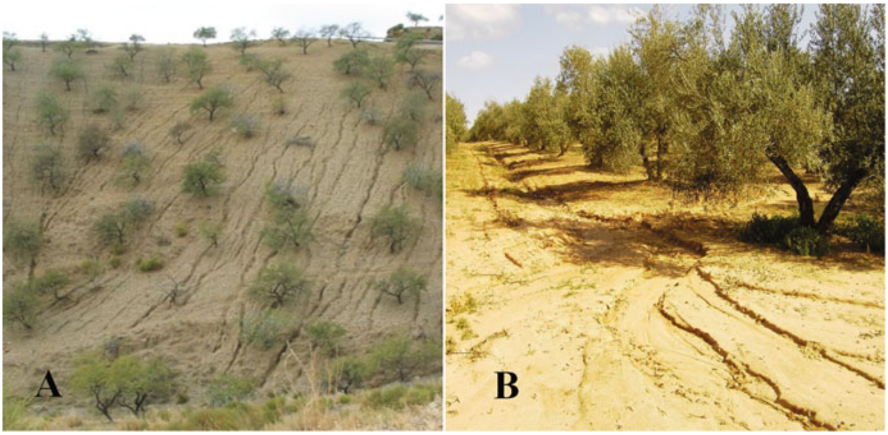


Fig. 13.4 Water erosion impact on almond (**a**) and olive (**b**) orchards

(Bienes et al. 2016). Also, the limited availability of water typical of the Mediterranean region hinders plant colonization in short periods (García-Ruiz et al. 2013), leaving the soil susceptible to erosion (Robledano-Aymerich et al. 2014). This period of vegetation cover lack, also called "window of adaptation", can trigger the rates of soil erosion, leading to severe soil degradation and the development of rills and gullies (Cerdà et al. 2018a).

Additionally, the increasing water scarcity in future as predicted due to climate change will affect agricultural systems of semi-arid Mediterranean areas (García Tejero and Durán Zuazo 2018; Malek et al. 2018). More frequent or prolonged climate droughts (less rain) and more agricultural droughts (drier soils) are forecast in the late twenty-first century. Agriculture is expected to be the economic sector that most suffers the impacts of water scarcity, as it represents 70% of global freshwater use according to FAO (2012). The FAO expects an increase in global food demand of approximately 50% by 2050, based on global trends in food preferences and the consequences of economic development, as well as population growth (FAO 2017). Furthermore, the demand for water from other sectors is also expected to increase, promoting competition for this resource, as well as augmentation in the imbalance between water supply and demand (Meena et al. 2020). Thus, the lack of water is one of the most severe threats to the Mediterranean region which requires adequate management (Iglesias et al. 2007).

As expected, climate change will be able to modify hydrological flows and the accessibility to fresh water, which will have an impact on both rainfed and irrigated agroecosystem (Turral et al. 2011; WWAP 2012). The projections made show a reduction in rainfall in semi-arid zones, as well as more variability in the distribution of rain, a higher frequency of extreme events and a rise in temperatures. And this will provoke a severe reduction in flow rates of water courses and aquifer recharge throughout the Mediterranean basin, which will affect the amount of water available for all uses (Green 2016; Smerdon 2017).

These limitations in the availability of water pressure to establish different strategies to improve the use of water in agriculture and that in the case of rainfed farms should focus on soil-management systems capable of improving the water retention capability of the soil. In rainfed systems, agricultural practices that allow the reduction of runoff losses, increasing infiltration, and storage of water in the soil; are the most appropriate strategies to optimize crop productivity (Kumar et al. 2019).

13.2.1 Mediterranean Rainfall and Soil Erosion

Warm and dry summers mainly characterize the Mediterranean climate, and cold and wet winters are the main feature of the Mediterranean climate (Fig. 13.5). Another of the main characteristics of the Mediterranean climate is the tremendous interannual rainfall variability, with years above or below average (García-Barrón et al. 2011). Also, intra-annual variability also exists, not surprisingly, that the precipitation of a few days of the year supposes a very high percentage of the total values of monthly and annual rainfall (Peñarrocha et al. 2002; García-Barrón et al. 2013).

The extreme events of high intensity are one of the distinctive features of the Mediterranean climate, mainly concentrated in spring and autumn. These events represent a very high percentage of annual rainfall and are one of the primary triggers of water erosion in the Mediterranean, having this region the highest rainfall erosivity factor ($R > 1000$ MJ mm ha^{-1} year^{-1}) in Europe (Panagos et al. 2015b).

As was stated before most of the annual soil losses are due to a few heavy rainfall events during the hydrological year (González Hidalgo et al. 2005; Ramos 2016). In vineyards in NE Spain, it was estimated that one or two incidents of high-intensity

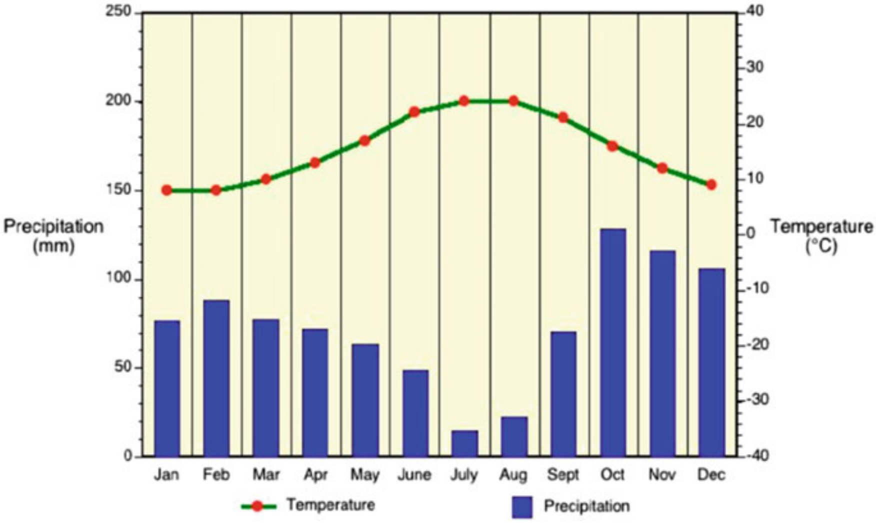


Fig. 13.5 Typical Mediterranean monthly temperature and precipitation

rainfall that are recorded per year generate about 75% of the total annual erosion (Ramos and Martínez-Casasnovas 2009). In this context, erosion rates higher than 10 Mg ha^{-1} have been recorded for a single event (Ramos and Martínez-Casasnovas 2015).

De Alba et al. (1998) showed the importance played by extreme episodes of high intensity in the erosion of agricultural soils in Mediterranean semi-arid regions, compared to events of moderate and low intensity but of high frequency. In a single isolated stormy episode, the average soil loss rate reached a value equal to 48 times the average annual erosion rate obtained in experimental plots. According to the findings, extreme events of high intensity are those that cause more than 84% of yearly soil losses and can reduce yields of permanent crops (olives, vineyards, almonds and others), which are of particular importance in the Mediterranean (Maracchi et al. 2005). Predictions about the effects of climate change in the Mediterranean establish a warmer climate with less total rainfall but more extreme rainfall events (Goubanova and Li 2007). Differences in the variability of several seasonal patterns of erosivity and the most erosive periods were reported by Verstraeten et al. (2006). According to Ramos and Durán (2014), it can be understood how erosive spring events increasingly aggravate annual soil losses. Annual records reflect how high erosion rates were caused by a reduced series of highly erosive events.

Besides, Diodato et al. (2011) in a study on how climate change has increased the aggressiveness of the precipitations in the Mediterranean concluded that climate change caused periods of greater exposure to erosive rains in almost all countries of the Mediterranean basin. In this line, the climatic tendency involves an increase in the frequency of extreme rainfall in shorter intervals of time, united to extended dry periods, which represents a particularly dangerous combination for soil erosion. Therefore, the importance of extreme events in erosion rates makes the duration of erosion studies critical. Since the probability of an extreme event is more significant during a longer-term field experiment, the average long-term rates are closer to the result of this type of experiments than to the short-term ones. Also, if an extreme event occurs during a short-lived experiment, the estimated erosion rate triggers, which makes it more challenging to compare trials of different duration (García-Ruiz et al. 2015).

13.3 Soil and Water Conservation Measures and Challenges

The need to develop sustainable management practices in agriculture is widely accepted (Marques et al. 2015; Sastre et al. 2017). The SWC techniques to improve water availability, increase agricultural production and reduce soil erosion and degradation are based on three mechanisms: (1) slope correction/flow velocity reduction (i.e., bench terraces, cover crops), (2) increases ground cover (i.e., cover crops, mulching) and (3) soil quality improvement (i.e., amendments, mulching).

In the EU, attempts have been made to promote and encourage more friendly agriculture with nature and the environment through the so-called conditionality, introduced by the reform of the Common Agricultural Policy in 2003. Thanks to this system, support payments to farmers were closely related to their compliance with animal welfare and food safety standards and their respect for environmental standards through the monitoring of Good Agricultural and Environmental Conditions (GAEC). EU member countries collaborate in preventing soil erosion and maintaining SOM—two of the GAEC requirements—through national and regional standards such as (1) ensure minimum maintenance of the soil cover, (2) limit the loss of soil through essential land management that reflects the specific conditions of the site and (3) promote appropriate practices that maintain the SOM level. The GAEC has helped in reducing land loss rates on farmland in member countries since its implementation. In general, the erosion has been reduced a 9.5% (from 2.7 to 2.4 t ha^{-1} $year^{-1}$). It is arable land signifies a more significant reduction in soil loss (average of 20.2%) thanks to the implementation of GAEC (EUROSTAT 2018).

The fear of farmers of possible adverse impacts that may result from the implementation of some conservation practices, such as the reduction of crop yields due to improper management of cover crops, has limited their application in some way (Marques et al. 2010; Ruiz-Colmenero et al. 2011; Ferreira et al. 2013; Meena et al. 2020a). According to Gómez (2017), one of the biggest impediments to implementing the use of temporary cover crops in Mediterranean tree crops, especially in rainfed systems, is this potential risk of yield reduction.

Therefore, in the management of the cover crop, the adaptation to the climatic characteristics of the area must be guaranteed to achieve a balance between crop production and soil conservation. The factors that must be taken into account are the timing of mowing of the cover, the selection of species and the frequency of tillage (Winter et al. 2018).

There are cultural factors that act as limitations in the adoption of the vegetation cover. For example, in the Mediterranean region for cultural and social reasons it is essential for the farmers' reputation not to have weeds in their fields (Cerdà et al. 2017; Sastre et al. 2017). Farmers do not accept the use of straw mulch because they consider it as a possible source of pests and diseases (Cerdà et al. 2018b).

The main challenges facing Mediterranean agriculture are to reduce soil loss and increase water availability, first of all, to find the appropriate SWC practices, taking into account the complexity of the Mediterranean landscape (García-Ruiz et al. 2013) is not possible to provide a single solution for all farms. Also, the agricultural policy must take into account this complexity of the Mediterranean environments and ecosystem services that are achieved with erosion reduction be integrated into subsidies (Galati et al. 2015). As asserted by Salvati (2010), incentives must take into account the multifunctional character of agriculture that implies a variable balance, at the regional and local level, between various economic, environmental and social functions. In practice, for farmers to adopt a measure, the minimum incentive they receive must be sufficient for it to be profitable.

Likewise, environmental policies must adapt to the new scenario set by climate change and promote the role of soil as a carbon sink (Meena et al. 2019). European farmers can implement measures to mitigate climate change with the adoption of soil conservation practices while obtaining a series of economic, environmental and social benefits. The predictions for the Mediterranean establish a reduction in the soil organic carbon (SOC) as a consequence of climate change (Muñoz-Rojas et al. 2017; Lagacherie et al. 2018). This loss of SOC results in soil degradation and associated ecosystem services (Lal 2004a), something especially serious in Mediterranean soils, already very depleted of carbon. For this reason, it is crucial for the conservation of Mediterranean soils in marginal areas to preserve their carbon reserves (Tommaso et al. 2018).

13.4 Impact of Hillslope Farming on Soils

Soil health is defined as the continued ability of the soil to function as a vital living ecosystem that supports plants, animals and humans. In this line, soil health covers three types of soil characteristics: biological, physical and chemical (Fig. 13.6). Retaining soil health and improved crop productivity are the two major challenges for sustainable agriculture and food security. In this context, soil management modified the soil physicochemical properties and its biodiversity. And the loss of SOM deteriorates soil structure, reducing the capacity of soil to storage water and increasing water losses by runoff. This minor water availability declines soil biomass and biodiversity, particularly in hilly farming areas.

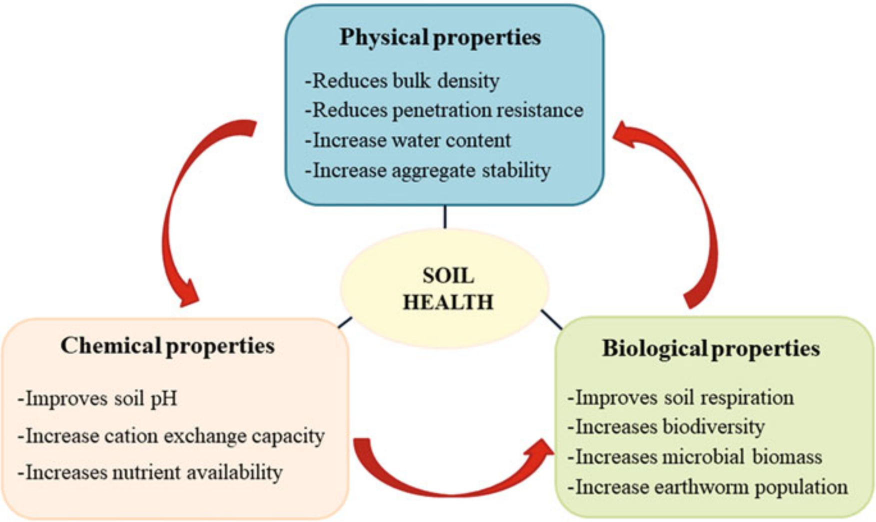


Fig. 13.6 Interactions among physical, chemical and biological properties on soil health

13.4.1 Physical Soil Parameters

Conventional tillage is an extensive soil-management practice used to break crusts on the soil surface, and therefore, provoking an important alteration of soil physical properties. Specific physical properties are affected to a greater extent by the soil-management system such as porosity, bulk density, hydraulic conductivity, absorption capacity and aggregate stability (Fig. 13.6) (García-Tejero et al. 2020; Kumar et al. 2020).

In the Mediterranean basin, the management of soils under tree crop has traditionally been done through surface tillage to reduce weed competition and break up surface crusts. Although initially, tillage reduces the apparent density of the soil, the long-term effect is the opposite since the passage of the machinery promotes the compaction of the soil and the formation of a ploughing layer (Van Dijck and Van Asch 2002; Lagacherie et al. 2006; Linares et al. 2014). Processes such as the deterioration of the structure and the compaction of the soil are favoured by the exhaustion of the SOM by intensive tillage, which causes the degradation of the soil (Abid and Lal 2009). As a result of the progressive compaction of the soil, porosity decreases, which implies a reduction in the infiltration and hydraulic conductivity of the soil, and therefore, the water storage capacity of the soil is reduced (Azooz and Arshad 1996). The implementation of soil-management strategies that reduces compaction concerning traditional tillage is of great importance, expressly in permanent crops, where the effects of tillage accumulate progressively over the years.

Persistent tillage creates the soil considerably more susceptible to crusting and sealing, by eliminating the protective effect of vegetation, and therefore, increasing the risk of water erosion in hillslope farming. When successive rains occur sometime after the soil was tilled, a superficial crust can be formed, which is characteristic of cultivated soils (Le Bissonnais et al. 2002). The impact of rainfall drop causes the breakdown of soil aggregates and the release of particles finer, which are redistributed by the near-surface and fill the most superficial pores. This process causes regular sealing and surface waterproofing, decreasing water infiltration, and consequently, promotes soil erosion and runoff development (Gucci et al. 2012).

According to Pires et al. (2017), no-tillage exists a more complex structure of pores than under conventional tillage which favour water infiltration reducing environmental problems such as soil erosion. The soil structure homogenization could explain these differences under conventional tillage, induced by disk ploughing (Marcolan and Anghinoni 2006), and the presence of an enormous amount of fissures and bio pores under no-tillage, caused by the more intense fauna activity (Pérès et al. 2010). But in certain soils, non-tillage can increase erosion and runoff rates as a superficial crust forms that reduce infiltration and hydraulic conductivity of the soil (Francia Martínez et al. 2006; Linares et al. 2014). That is why in certain semi-arid agroecosystems the tillage operations are necessary for soils that are prone to compaction to guarantee optimum production in rainfed orchards (Martínez-Mena et al. 2013).

Numerous studies have shown how the use of cover crops in a Mediterranean environment enhances the physical qualities of the soil, such as improved soil structure, reduced compaction, increased infiltration rate, etc. (Celano et al. 2011; López-Piñeiro et al. 2013; Linares et al. 2014; Palese et al. 2014).

13.4.2 Chemical Soil Parameters

The physical, as well as chemical soil properties are directly influenced by microbiological processes that foster water-holding capacity, nutrient cycling, water availability, pH buffering, infiltration and cation exchange capacity (Fig. 13.6).

The soil is the main terrestrial reservoir of nutrients such as nitrogen, phosphorus, potassium, organic carbon, among others. Water erosion causes their mobilization, and therefore, significantly impacts on the carbon and nutrient cycles (Quinton et al. 2010). The highest concentration of organic matter in the soil is found on the surface because it is where the accumulation of plant debris occurs, thereby the erosion of the surface layer significantly reduces the SOM, affecting soil productivity (Pimentel and Burgess 2013).

The quantity and quality of the SOC stock are one of the defining characteristics of a soil (Manlay et al. 2007). One of the most useful indicators to measure soil degradation caused by erosion is to observe the evolution of the SOC pool (Rajan et al. 2010). The transport of organic carbon and nutrients through sediments is greatly influenced by the management of the farm's soil. Traditional soil management in the Mediterranean fruit crops consists of eliminating weeds through tillage, resulting in soils with compaction problems and high runoff rates. Loss of nutrients, either dissolved in runoff water or adsorbed to sediments, means a reduction in soil fertility (Zalidis et al. 2002), soil degradation as well as causing eutrophication and downstream contamination (Cooper et al. 2013; Rickson 2014; Dupas et al. 2015).

The accumulation of SOC in the soil occurs when the income (organic debris) is higher than the losses (erosion, mineralization and leaching) (Lal 2004b). Conservation agriculture (CA) enables a net increase in the carbon stock, compared to traditional tillage, by reducing the mineralization of SOM (López-Piñeiro et al. 2013; Nieto et al. 2013; Belmonte et al. 2018). The periodic disturbance of the soil structure and the subsequent drying-rewetting cycles to which the soil is exposed with the tillage, as well as exposing the retained organic matter in the micro-aggregates causes the rates of decomposition of the SOM increasing with tillage (Balesdent et al. 2000; Paustian et al. 2000). The greater incorporation of plant residues, as well as the decomposition of the roots involved in the use of cover crops, increases the SOC (Amézketa 1999; Faucon et al. 2017). Alternative soil-management systems to tillage, such as non-tillage or the use of cover crops, reduce soil losses due to erosion and improve fertility (Rodríguez-Lizana et al. 2008; Gómez et al. 2009). In this sense, there are various studies found improvements in SOM and plant nutrients in Mediterranean fruit crop orchards, through CA practices (Ruiz-Colmenero et al. 2011; Montanaro et al. 2012; Almagro et al. 2016; Keesstra et al. 2016b; García-Díaz et al. 2017).

13.4.3 Biological Soil Properties

Soil quality usually relates to chemical and physical soil properties, however, the distinction between soil quality and soil health is that the soil health takes into account that soil is dynamic. In this context, the organisms within the soil are just as vital as what crops are growing above the soil. Therefore, soil organisms have the capacity to enhance soil structure, repel plant disease and make nutrients affordable to crops (Fig. 13.6). Consequently, the soil quality, its productivity and the ecosystem services provided by the soil benefit from certain activities of the soil biota (Barrios 2007; Adhikari and Hartemink 2016). In this line, some of these beneficial activities for the soil are the recycling of nutrients, the increase of infiltration capacity through the earthworm tunnels or plant roots, the mixture of soil components that favours its formation and productivity, improves the firmness of soil aggregates through plant exudates and prevents sealing of soil surface (Spurgeon et al. 2013; Capowiez et al. 2014; Bertrand et al. 2015).

Researchers estimate that at least about one-quarter of species on planet earth live in soils. Land degradation causes soil biodiversity to decline (IPBES 2018). The biological diversity of an ecosystem is determined by the amount of organic matter, living or not, present in it (Wardle et al. 2004). When soil is degraded by decreasing the SOM and its overall quality, the biomass productivity of the ecosystem decreases, being crucial, in this context, the role of plant cover in soil protection against erosion (Durán Zuazo and Rodríguez Pleguezuelo 2008; Lal 2015). Among the threats to soil biodiversity, the loss of SOM due to agricultural intensification and land use changes are considered significant drivers (Gardi et al. 2013).

The functioning of agroecosystems depends mainly on soil biodiversity and SOC content. These parameters significantly influence the ability of the soil to mitigate climate change, store water and produce food (Fig. 13.7) (Wall et al. 2015). Globally, the value of ecosystem services provided by soil biodiversity is estimated at between 1.5 and 13 billion dollars annually (Laban et al. 2018). The multifunctionality and sustainability of the ecosystem can be threatened by the loss of soil biodiversity and/or changes in soil biological communities (Wagg et al. 2014).

The negative impact on soil quality and biodiversity of traditional soil-management systems is widely accepted. Through two of the basic principles of the CA, such as the minimal disturbance of the soil and the use of plant covers, this impact can be minimized, being a viable option for soil conservation (Sánchez-Moreno et al. 2015; Jackson et al. 2019). Several studies have proved how soil conservation practices in permanent crops in the Mediterranean region, such as reduced tillage or cover cropping, can increase soil biodiversity and microbiological activity (Ramos et al. 2010; López-Piñeiro et al. 2013; Henneron et al. 2014; Simoes et al. 2014; Belmonte et al. 2018).

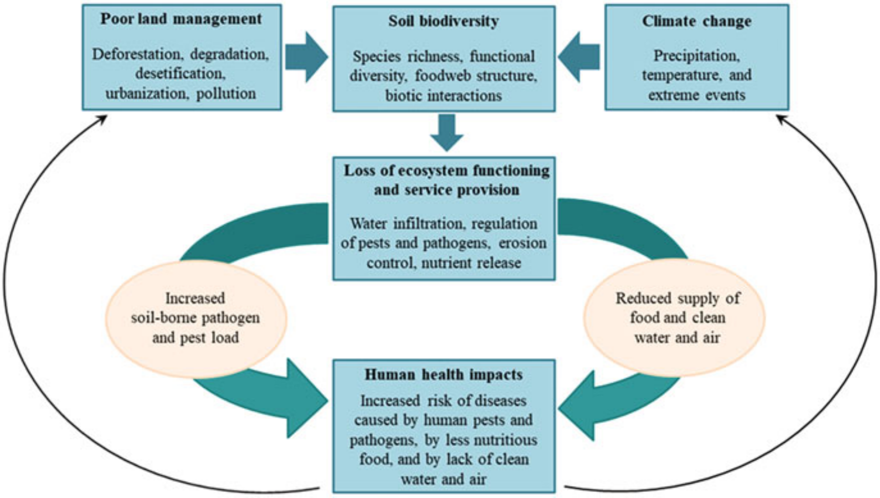


Fig. 13.7 Impacts produced by the loss of soil biodiversity

13.5 Conservation Agriculture for Hillslope Farming

Tillage is shown as a soil-management system unable to maintain current production levels or to sustainably increase production (Pisante et al. 2012). It is because tillage causes soil degradation, reducing its productive capacity and negatively affecting the ecosystem services provided by the soil (Montgomery 2007; Lal and Stewart 2013).

Conservation agriculture is the principle of the crop production system that promotes in situ water conservation and the reduction in erosion driven soil loss. The CA is proposed as a different option to conventional management to ensure a better balance in the ecosystem services provided by the soil (Caron et al. 2014). The fundamental objective of the CA is to achieve sustainable land use through SWC (Lal and Stewart 2013) and constitutes the central focus of FAO's new sustainable agricultural intensification strategy (FAO 2011). This strategy adopts an ecosystem approach to improve resilience, productivity and the flow of soil services while mitigating climate change by reducing emissions from the agricultural sector. The CA originated in the 1930s in the USA to combat soil desertification caused by water and wind erosion (Holland 2004). The principles on which the CA is based are to maintain soils with permanent vegetation cover, non-tillage to reduce soil alteration and increase the diversity of plant species, as shown in Fig. 13.8 (FAO 2014). The CA improves the biodiversity and biological processes of the soil, which makes the use of water and nutrients of the soil more efficient and promotes a sustainable crop production.

Globally, the CA was practiced in 2015/16 on approximately 180 million ha of farmland, which represents 12.5% of the total world farmland (Kassam et al. 2019). Since 2008 the annual increase rate of the CA has been about 10 million ha per year

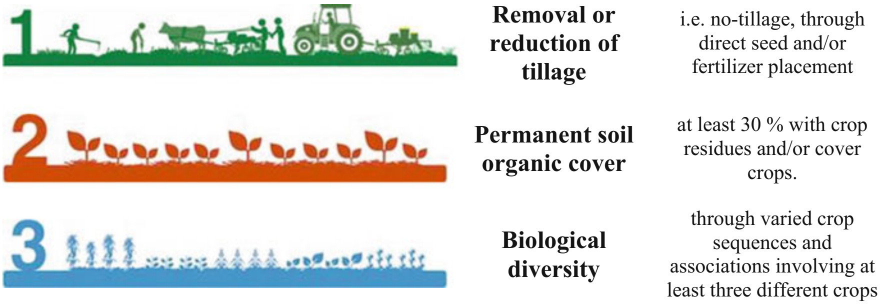


Fig. 13.8 Three principles of conservation agriculture

(Kassam et al. 2015), showing that this alternative production system has a growing interest for governments and farmers worldwide.

The implementation of CA has occurred mainly in North and South America as well as in Australia and Asia (Friedrich et al. 2012). In Europe (except Russia and Ukraine), the implantation of CA in farms is low compared to other regions of the world, with 3.6 million ha under CA in 2015/2016 (Kassam et al. 2019), what involves 5% of its total cropland, mainly located in Spain (over 25% of the entire European CA area), followed by United Kingdom (10%), France and Italy (8%, both) (Kassam et al. 2019).

In countries such as Spain and Italy, the area under CA has increased under perennial crops such as vines and olives. For Spanish case, there was a 54% increase in the implementation of plant covers in soils with perennial fruit crops in the period 2006–2013 (González-Sánchez et al. 2015). Several reasons explain why the adoption of CA in Europe has been slower. Among other reasons, we can highlight the EU's agricultural policies, the moderate climate and the opposition of specific interest groups (Jat et al. 2014). In Europe, the loss of productivity associated with land degradation, the increase in production costs and the need to adapt to the possible impacts of climate change have been the drivers of the CA in recent years (Kassam et al. 2014).

Figure 13.9 shows the environmental impacts of conventional and the benefits of CA on the soil system. The conversion to CA involves a series of variable benefits that depend on many factors such as agroclimatic conditions, the properties of the soil, the characteristics of the farm, the training and experience of the farmer, etc. (Kassam et al. 2014). The functions of the soil are the result of the interaction of various factors: edaphoclimatic, land use and management practices; what makes the benefits that occur are variable (Mueller et al. 2010; Schulte et al. 2015; Coyle et al. 2016). There are certain economic and environmental benefits attributed to the CA, which are widely accepted and summarized in Table 13.1.

Many studies have shown that CA in the Mediterranean basin allows improving the properties of the soil and the ecosystem services provided by it (Kassam et al. 2012; Ghaley et al. 2018; Lee et al. 2019).

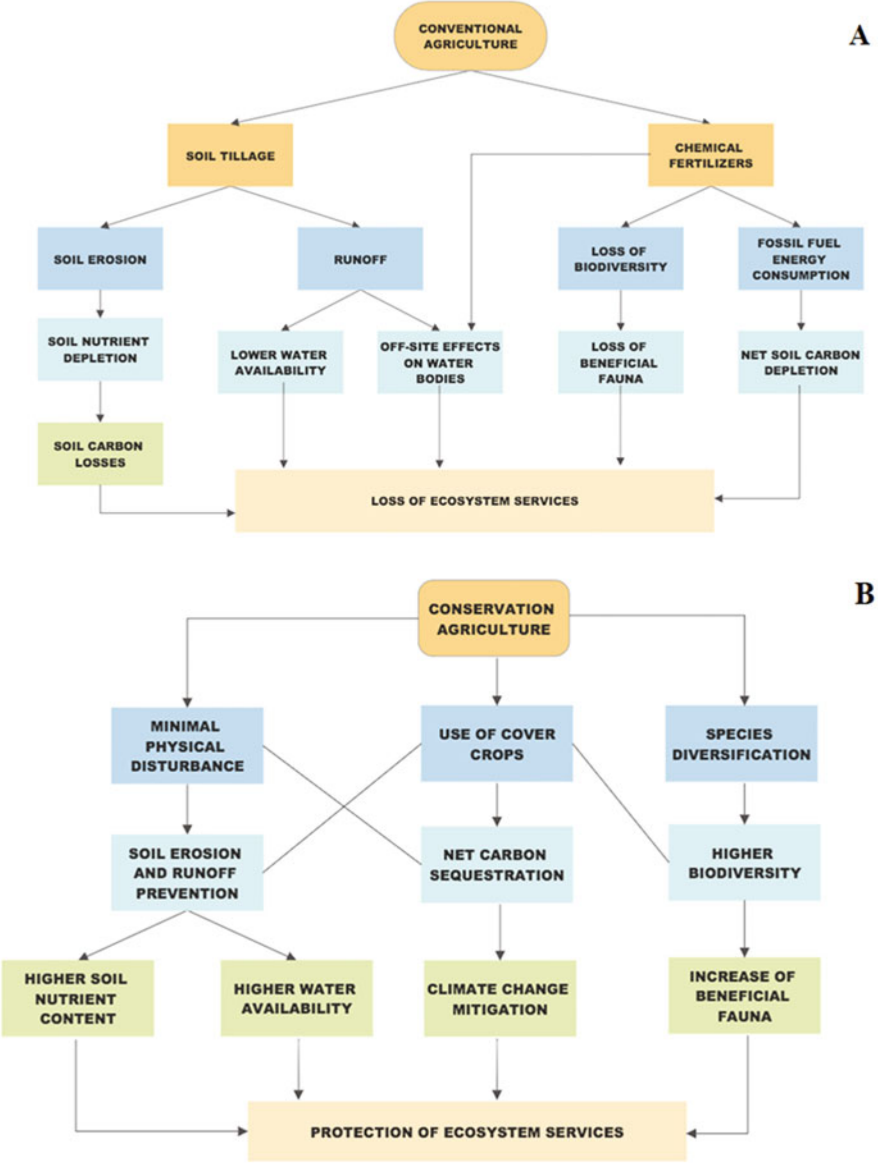


Fig. 13.9 Environmental impacts of conventional agriculture (**a**) and the benefits of conservation agriculture (**b**) on soils

Table 13.1 Main economic and environmental benefits generated by the conservation agriculture

Economic	Environmental
Labour and fuel saving	Amelioration of soil properties
Cost-saving	Increase of soil biodiversity
Augmentation of yields	Erosion and surface runoff reduction
Less off-site problems	Less CO_2 emissions
	Enhancement of the CO_2 sink effect of the soil
	Less pollution of downstream water

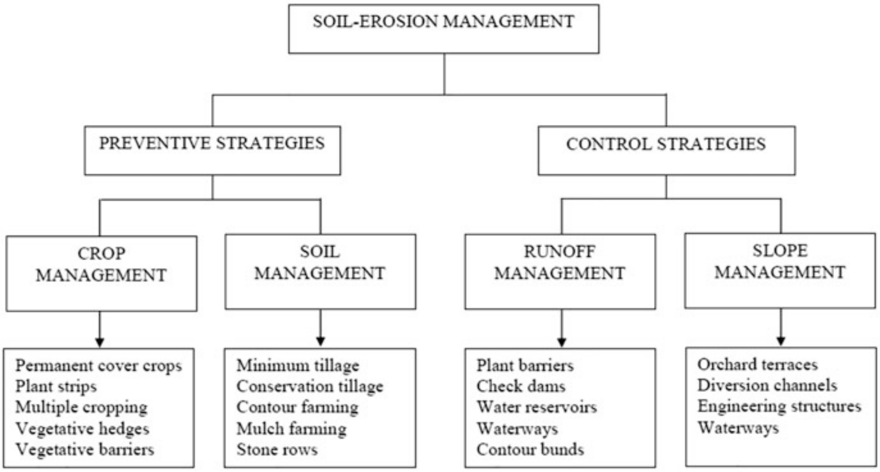


Fig. 13.10 Preventive and control strategies to soil-erosion management

13.5.1 Plant-Nutrient Transport by Soil Erosion and Runoff

The surface covering of soil with plant covers reduces the soil erosion and runoff, for many reasons: (1) soil cover avoids direct impact of raindrops and the breakdown of aggregates (2) vegetation acts as a physical barrier and slows water movement downslope and (3) infiltration rate increases to improve soil structure, this implies a reduction in the agricultural runoff. In the long term, the increase in organic matter by plant covers contributes to increasing the cohesion of aggregates and soil stability, as well as to improve water infiltration (Durán Zuazo and Rodríguez Pleguezuelo 2008).

Figure 13.10 presents the preventive and control strategies for soil-erosion management. Surface runoff is one of the critical factors governing rill erosion and gully development, and concentrated erosion takes place where flow erosion energy is intense. Under this situation, when rainfall intensity surpasses infiltration capacity, flow erosion arises.

Soil loss can be much reduced to a great extent by adopting SWC techniques than runoff (Maetens et al. 2012b). Gómez (2017) tested the role cover crops in soil loss

Table 13.2 Nutrient fluxes with surface runoff under different agricultural systems in olive orchards

	$N\text{-}NO_3$	$N\text{-}NH_4$	$P\text{-}PO_4$	K
	(mg m^{-2})			
Conventional system				
Average	100.3 ± 211.5	7.8 ± 5.9	2.8 ± 2.6	9.3 ± 6.5
Maximum	658.7	17.3	8.1	19.1
Minimum	0.5	1.2	0.4	1.9
Total	1003.2	77.8	28.3	92.9
Conservation system				
Average	22.5 ± 25.5	5.8 ± 7.3	1.7 ± 2.5	5.7 ± 7.1
Maximum	74.8	24.8	7.8	22.2
Minimum	0.3	0.0	0.0	0.1
Total	359.3	98.0	27.7	97.6

± standard deviation, NO_3 nitrate, NH_4 ammonium, PO_4 phosphate; *K* potassium

reduction and found an average reduction of about 60% in olive and vineyards at the plot scale. The effect of cover crops on the decrease in average annual runoff is not clearly identified; although the average reduction was approximately 25% and it is site-dependent.

The reason that explains these different responses are that while the reduction in soil losses is due to physical protection by cover crops, the mechanism that controls infiltration is more complex and varied with sites (Gómez et al. 2011). In orchards where soil infiltration is limited by surface sealing or reduced porosity, the roots have a definite effect on reducing runoff, however, when infiltration is controlled by saturation of the soil profile, the impact of cover crops is limited.

Table 13.2 presents the results for nutrient transport (nitrate, ammonium, phosphate and potassium) per area by a runoff for the two agricultural systems in rainfed olive orchards (Durán Zuazo et al. 2015a), showing significant reductions under conservation system during the two-monitoring season in SE Spain. In this way, it has far-reaching consequences in the sense that the control of pollution from erosion is crucial in lessening the eutrophication of both surface and groundwater situated in lowlands.

On the other hand, Durán Zuazo et al. (2015b) highlighted the positive impact of plant strips (barley, spontaneous vegetation, thyme and vetch) on control of soil erosion and runoff in hillslopes with olive (Table 13.3), almond (Table 13.4) and vineyards (Table 13.5), revealing the benefits of CA interventions, and its further implications to encourage soil productivity and its sustainability.

Nutrient loss through erosion processes generates a series of effects both on and off the site. One of the on-site impacts is the decrease in nutrient availability. The loss of soil indirectly impoverishes the upper soil layer because significant amounts of organic matter and nutrients are carried away with sediments. Therefore, there is a loss of soil fertility and, as a consequence, a reduction in crop yields (García-Díaz et al. 2016).

Table 13.3 Soil erosion and runoff response to conservation agriculture techniques in rainfed olive orchards during the three monitoring season

Year	Rainfall (mm)	NTBS		NTSVS		NT	
		Soil erosion (t ha^{-1})	Runoff (mm)	Soil erosion (t ha^{-1})	Runoff (mm)	Soil erosion (t ha^{-1})	Runoff (mm)
1	348.9	5.61	7.4	5.64	12.1	14.5	164.3
2	449.4	8.69	9.6	14.9	8.8	34.2	147.0
3	350.5	0.64	5.9	0.72	5.0	3.3	108.8
Mean	382.9	4.98	7.6	7.11	8.6	17.3	140.0
s.d.	57.6	4.06	1.9	7.24	3.6	15.7	28.4

s.d. standard deviation, *NTBS* non-tillage with barley strips, *NTSVS* non-tillage with spontaneous vegetation strips, *NT* non-tillage without plant strips

Table 13.4 Runoff and soil erosion response to conservation agriculture techniques in rainfed almond plantations throughout 30 rainfall events

	Rainfall (mm)	Runoff (mm)			Soil erosion (kg ha^{-1})		
		MTTS	MTSVS	MT	MTTS	MTSVS	MT
Mean	24.6	0.4	0.3	0.4	21.4	17.5	26.5
s.d.	14.5	0.4	0.2	0.4	47.3	24.9	57.2
Max.	62.0	2.1	0.8	2.0	238.5	83.6	307.0
Min.	2.6	0.0	0.0	0.0	0.2	0.0	0.1
Total	739.0	11.8	8.2	11.1	642.2	525.6	794.4

s.d. standard deviation, *NTBS* non-tillage with barley strips, *NTSVS* non-tillage with spontaneous vegetation strips, *NT* non-tillage without plant strips

Table 13.5 Conservation agriculture techniques in rainfed vineyard in relation to water erosion during 26 rainfall episodes

	Rainfall (mm)	Runoff (mm)			Soil erosion (kg ha^{-1})		
		MTCVS	MT	MTBS	MTCVS	MT	MTBS
Mean	29.1	4.8	4.1	3.4	394.2	416.7	162.3
s.d.	18.9	9.8	11.5	6.8	1576	1910	426.9
Max.	91.3	47.8	59.2	33.0	8087	9775	2129
Min.	11.0	0.0	0.0	0.0	0.1	0.0	0.1
Total	757.0	124.5	107.9	89.7	10,247	10,835	4219

s.d. standard deviation, *MTCVS* minimum tillage with common vetch strips, *MT* minimum tillage without plant strips, *MTBS* minimum tillage with barley strips

Improper soil management generates additional costs for farmers who have to replace nutrient loss and minimize erosion-induced productivity reduction (Pimentel et al. 1995). Large amounts of fertilizers are applied to compensate for nutrient losses and ensure crop production, Martínez-Casasnovas and Ramos (2006) estimated that farmers should allocate 2.4 and 1.2% of annual income from the sale of grapes to replace the nitrogen and phosphorus lost by erosion, respectively. Among the off-site effects are the ecological impacts on watercourses because of excessive

Fig. 13.11 Plant strips in olive orchards (**a**) controlling agricultural runoff and vineyard and almond orchards (**b**) with bare soil increasing risk of pollution of water bodies

sedimentation and associated pollutants (Boardman et al. 2019). The pollution of water bodies by herbicides and fertilizers is an off-site effect of water erosion (Fig. 13.11). Other effects are the eutrophication of reservoirs, damages to infrastructures and an increase in flood damages due to sediment carried away by the flows (Gómez et al. 2014).

Sediments show nutrient and organic matter enrichment rates (Marques et al. 2008; Ruiz-Colmenero et al. 2011; Endale et al. 2017). It can be attributed to the enrichment of clays in sediments (Martínez-Mena et al. 2012) since fine-sized particles are more easily transported by erosion. The clay fraction of the soil (<2 μm) is eroded preferentially, and the nutrients in the soil are lost adsorbed or contained in these particles (Nie et al. 2015; Zhang 2016).

Various works show that CA reduces the number of dissolved nutrients in runoff or adsorbed in sediments (Ruiz-Colmenero et al. 2011; Biddoccu et al. 2016; García-Díaz et al. 2017). In this line, Gómez et al. (2009) reported a significant reduction of nutrient losses by cover crop treatment respect to conventional tillage. Similarly, Francia Martínez et al. (2006) controlled erosion, runoff and nutrient loss on a hillslope of 30% with olive *cv*. Picual from different soil-management strategies: (1) non-tillage with barley (*Hordeum vulgare*) strips (BS); (2) conventional tillage (CT); (3) non-tillage without plant strips (NT) (Table 13.6). Therefore, the total NPK losses (sediments and runoff) from BS were 0.87, 0.07 and 0.72 kg ha^{-1}, from CT 1.82, 0.11 and 0.97 kg ha^{-1} and from NT 3.15, 0.29 and 2.45 kg ha^{-1}, respectively. The protective effect of CA measures is especially important in extreme events, typical of the Mediterranean climate, in which very high nutrient fluxes can be recorded. Ramos and Martínez-Casasnovas (2006) measured a loss of 109 kg N ha^{-1}, 109 kg P ha^{-1} and 36 kg K ha^{-1} in one single storm in a vineyard plantation; these amounts represent 12.5, 60.5 and 10.2%, respectively, of the annual application of these plant nutrients.

Table 13.6 Average monthly plant nutrients in runoff and sediments from BS, CT and NT plots during the 2-year monitoring period

	Runoff (mg l^{-1})											
	BS				CT				NT			
Month	N-NO_3	N-NH_4	P-PO_4	K	N-NO_3	N-NH_4	P-PO_4	K	N-NO_3	N-NH_4	P-PO_4	K
Jan.	9.7 ± 0.0	1.3 ± 0.0	0.2 ± 0.0	1.0 ± 0.0	–	–	–	–	5.5 ± 2.7	1.8 ± 1.2	0.4 ± 0.2	1.6 ± 0.7
Mar.	0.1 ± 0.0	6.2 ± 0.0	0.1 ± 0.0	6.2 ± 0.0	–	–	–	–	0.2 ± 0.0	4.1 ± 0.0	2.3 ± 0.0	3.4 ± 0.0
Apr.	5.5 ± 4.3	1.2 ± 0.1	0.5 ± 0.3	1.6 ± 0.4	–	–	–	–	5.6 ± 3.5	2.5 ± 1.3	0.3 ± 0.1	1.9 ± 0.7
May	14.5 ± 11.3	0.8 ± 0.6	0.9 ± 0.5	3.1 ± 2.0	6.30 ± 7.1	7.3 ± 6.4	2.7 ± 2.5	5.2 ± 0.6	15.5 ± 0.0	4.6 ± 0.0	0.3 ± 0.0	1.5 ± 0.0
Sep.	–	–	–	–	–	–	–	–	9.9 ± 0.0	1.9 ± 0.0	0.9 ± 0.0	1.5 ± 0.0
Oct.	9.5 ± 7.1	3.9 ± 2.2	0.7 ± 0.2	2.6 ± 0.8	25.5 ± 23.4	3.7 ± 2.8	0.6 ± 0.2	2.8 ± 1.1	7.4 ± 2.8	5.8 ± 5.6	0.5 ± 0.3	2.1 ± 1.2
Nov.	14.1 ± 0.0	3.2 ± 0.0	0.5 ± 0.0	2.1 ± 0.0	5.36 ± 0.0	0.7 ± 0.0	0.4 ± 0.0	1.60 ± 0.0	10.9 ± 0.0	0.7 ± 0.0	0.3 ± 0.0	1.7 ± 0.0
Dec.	5.6 ± 1.5	2.2 ± 0.8	0.5 ± 0.4	2.1 ± 0.6	1.3 ± 1.1	1.8 ± 0.9	0.4 ± 0.3	1.8 ± 1.5	6.7 ± 2.0	2.9 ± 1.2	0.5 ± 0.3	1.8 ± 0.6

Sediments (μg g^{-1})												
			P^*				P				P	
Jan.	4.7 ± 2.1	19.3 ± 4.3	10.5 ± 0.0	140 ± 0.0	–	–	–	–	24 ± 0.0	114 ± 0.0	11.8 ± 0.0	70 ± 0.0
Mar.	–	–	–	–	–	–	–	–	–	–	–	–
Apr.	6.2 ± 1.8	23.4 ± 5.8	15.9 ± 0.0	215 ± 12	–	–	–	–	6.0 ± 0.8	72 ± 54	19.3 ± 16.4	125 ± 63
May	17.5 ± 0.0	45.9 ± 0.0	10.1 ± 6.5	136 ± 58	21.4 ± 0.0	34.1 ± 5.5	11.7 ± 0.0	80 ± 7.0	113 ± 102	53 ± 14	10.5 ± 2.4	77 ± 17
Sep.	–	–	–	–	–	–	–	–	–	–	–	–
Oct.	4.5 ± 5.8	65.1 ± 33.2	9.6 ± 3.2	135 ± 20	3.7 ± 3.4	42.3 ± 1.2	12.3 ± 2.7	123.3 ± 5.8	4.6 ± 3.1	78 ± 56	11.8 ± 3.1	70 ± 7.9
Nov.	13.6 ± 0.0	20.7 ± 0.0	7.5 ± 0.0	80 ± 0.0	–	–	–	–	59 ± 0.0	22 ± 0.0	10.9 ± 0.0	60 ± 0.0
Dec.	9.3 ± 3.2	70.4 ± 14.9	12.8 ± 1.1	132 ± 46	9.9 ± 2.0	49.5 ± 0.0	11.7 ± 3.4	134 ± 17	5.9 ± 3.1	66 ± 27	17.6 ± 7.3	116 ± 69

BS non-tillage with barley strips, *CT* conventional tillage, *NT* non-tillage without plant strips, ± standard deviation; – without samples * available phosphorus

13.5.2 Soil-Water Content

CA is especially beneficial in rainfed agricultural systems, where the amount of rainfall and its distribution is what determines the availability of water, mainly in regions such as the Mediterranean basin with a very irregular distribution of rainfall and frequent periods of drought (García-Tejero et al. 2020). In rainfed systems, the only method of improving water availability is adequate soil management to optimize the rainwater harvesting. In areas where water is a crucial resource, conservation of water reservoir content is a relevant factor for agricultural production (Rockström et al. 2010), especially during the dry season (Gómez et al. 2014). The techniques used to reduce water loss due to runoff can contribute to more efficient use of water, which can lead to increased production, especially in drier regions such as the Mediterranean (Maetens et al. 2012a).

The increase in SOC reserves with CA produces an improvement in soil structure and distribution of porosity, which could increase water infiltration and, in turn, the storage capacity of soil water. The structural remodelling of the soil in the CA systems improved water infiltration, increasing the recharge of the deeper layers that, for the most part, supply water to the crops in rainfed conditions, especially during the dry summer months (Palese et al. 2014). For example, in the Mediterranean dryland olive grove, an increase in SOC ~1.0 to 1.4% improved macroporosity, which contributed to increasing the saturated hydraulic conductivity of the soil. The improvement in infiltration through improving SOC content contributed to a 34% increase in the water stored in the soil compared to those with low SOC (Montanaro et al. 2017).

A rainfed fruit orchard with cover crops consumes more water than one tilled, although it can improve the intercepting and storing rainwater in the soil (Celano et al. 2011). Therefore, the appropriate management of cover crops needs to prevent water competition with tree crops. The use of selected vegetation, protection strips and inert padding can be combined to try to minimize the risk of competition for water between the cover and the crop, and thus achieve a balance between soil conservation and productivity (Gómez et al. 2014).

In this context, Durán Zuazo et al. (2009) showed that crop strips reduced runoff and increased infiltration through two mechanisms: interception by the cover and subsequent cortical flow. Therefore, during each season the mean soil-water content beneath the trees (SWC-bt) was higher than the mean soil-water content in plant strips (SWC-st) for the treatment with plant covers (Fig. 13.12). Experimental conditions with 30% slope and relatively low soil permeability encouraged lateral subsurface flow and, therefore, the percentage of water available for tree roots was higher.

In the Mediterranean agricultural areas, CA has yield advantages, especially during dry years, when conservation techniques increase water supply and improve the yield stabilization (Bravo et al. 2007; Vastola et al. 2017).

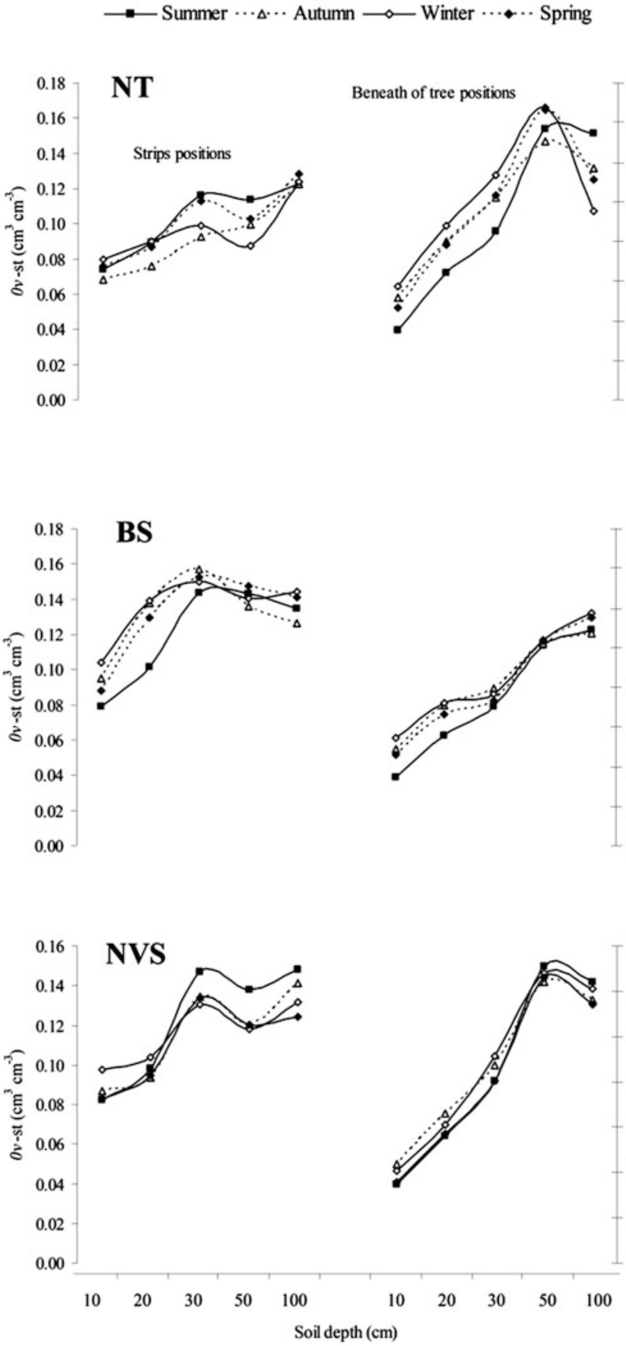


Fig. 13.12 Average seasonal soil-water contents at plant strip and beneath of olive tree positions subjected to different soil-management strategies. *NVS* non-tillage with native vegetation strips, *BS* non-tillage with barley strips, *NT* non-tillage without plant strips

13.5.3 Soil Organic Carbon Contents

Most Mediterranean soils exhibit low (≤2%) or very low (≤1%) SOC content, particularly in the southern side of the Mediterranean, with a mean SOC about 1.1% in the top 0–30 cm of soil depth (García-Ruiz et al. 2013; Henry et al. 2009). This limited SOC in the Mediterranean region is due to various factors, standing out for its relevance to climate and soil management (Lagacherie et al. 2018). Regarding the weather, high summer temperatures stimulate rapid mineralization of plant debris, and rainfall scarcity limits the ecosystem primary productivity and soil carbon accumulation. And concerning soil management, in the Mediterranean, the most commonly used techniques contribute little organic matter to the soil and cause accelerated mineralization of organic matter and its loss (Fig. 13.13) (Lal 2004a).

In this sense, Durán Zuazo et al. (2014) showed in a small watershed as the land use, and the associated management practices exert substantial impacts upon SOC stocks. Table 13.7 displays the types of land use investigated, being the highest average SOC stocks were recorded in forests, shrubland and grasslands, in contrast to the abandoned farmlands that presented the lowest values and agricultural uses with an intermediate value.

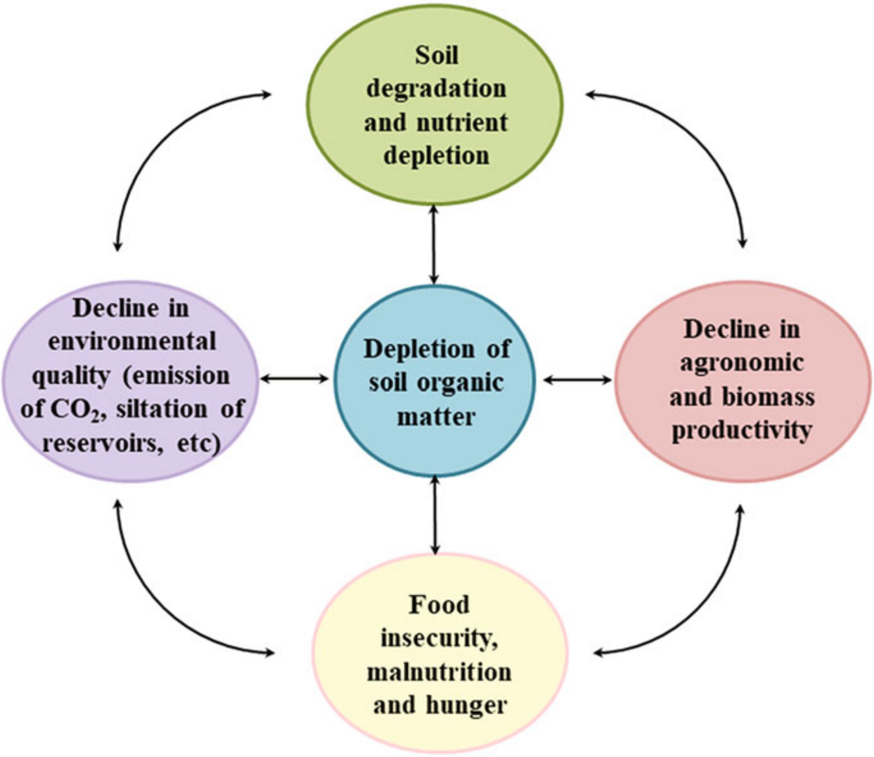


Fig. 13.13 The vicious cycle of depletion of soil organic matter

Table 13.7 Average soil organic carbon in relation to different land uses in semi-arid Mediterranean area

Land use/land cover	SOC content (kg m^{-2})
Forest/*P. halepensis*	10.03 ± 0.43 a
Forest/*P. sylvestris*	8.31 ± 0.37 a
Shrubland	7.20 ± 0.78 a
Grassland	6.34 ± 0.31 a
Farmland/Olive	5.10 ± 0.76 ab
Farmland/Almond	4.88 ± 0.69 ab
Farmland/Cereals	5.29 ± 0.52 ab
Abandoned farmland	2.80 ± 0.53 b

Values with different letters are statistically different at $p < 0.05$ by LSD test (least significance difference); ± standard deviation

The increment in SOC is of particular interest in the Mediterranean agroecosystems, as it improves physical, chemical and biological soil properties (Lal et al. 2011), helping to strengthen resilience for adaptation to climate change and contributing to mitigation by acting as a carbon sink (Aguilera et al. 2013). The CA increases SOC stock through a positive balance between inputs and outputs of carbon through the reduction of SOC losses by oxidation, the increase of organic carbon inputs to the soil, or a combination of both factors (Six et al. 2004). Losses can be reduced by reducing soil disturbance, either through non-tillage or through conservation tillage with practices that prevent soil inversion and limit the depth of tillage. The inputs of organic matter can be increased through the application of amendments or degradation of crop residues left on the soil.

The soil can store a limited carbon amount, and after the implementation of CA techniques the SOC content increases rapidly only during the first 10 years, and after this period the increase is practically zero, indicating that soil balance has been achieved (González-Sánchez et al. 2012).

13.6 Major Fruit Crops in the Mediterranean

The Mediterranean basin has long been a site of fruit and nut production. Due to the characteristics of climate, the fruit species grown in the region, attending to thermal needs, are temperate or subtropical climate species. The main fruit crops in the Mediterranean region are: olive, grapevines, almond, citrus, apricot (*Prunus armeniaca* L.), cherry (*Prunus avium* L.), plum (*Prunus domestica* L.), peach (*Prunus persica* (L.) Batsch), nectarine (*Prunus persica* var. nucipersica), apple (*Malus domestica* Borkh.), pear (*Pyrus communis* L.), walnut (*Juglans regia* L.), pistachio (*Pistacia vera* L.), etc. Figure 13.14 shows the area dedicated to these crops worldwide and in the Mediterranean basin in 2017, being the olive, almond and vineyard as most important crops.

According to EUROSTAT (2019a) a 14.8% of all the EU's farms were fruit orchards in 2016. Three member states, Romania, Spain and Italy, have the majority of EU's fruit orchards, with 21.6, 17.1 and 14.8% of the EU total, respectively. In

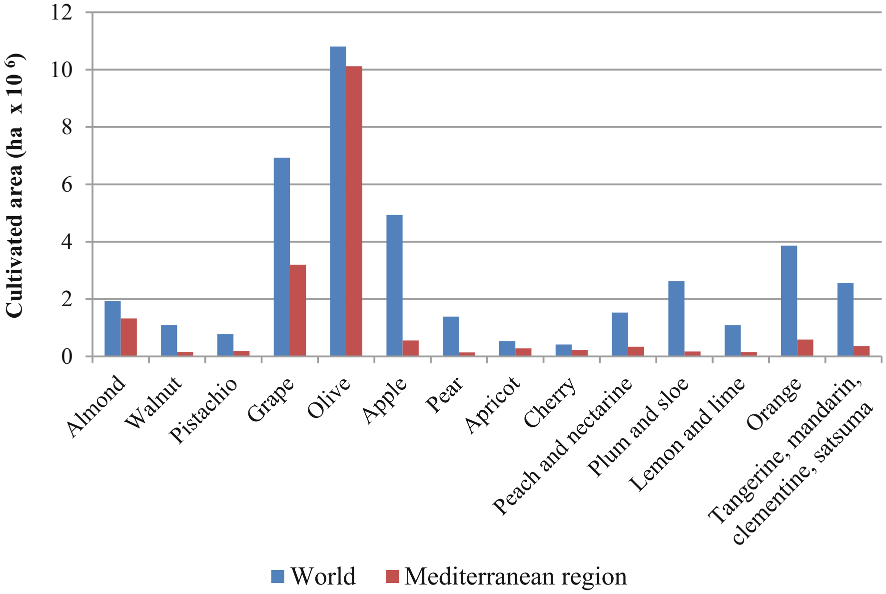


Fig. 13.14 Fruit crops area in 2017 (FAOSTAT 2019)

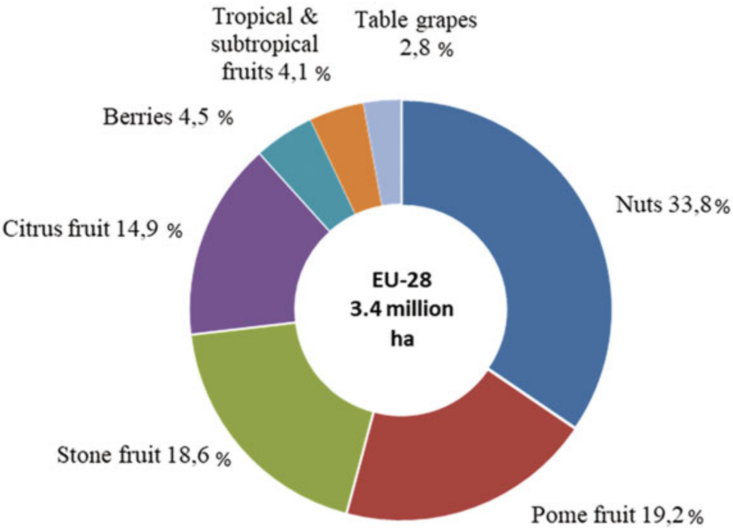


Fig. 13.15 Production area of fruit trees, EU (2017)

2017 there were in the EU about 3.4 million hectares dedicated to fruit trees, which represents 1.9% of the occupied agricultural land. Figures 13.15 and 13.16 show the distribution of this area by type of fruit tree and by country.

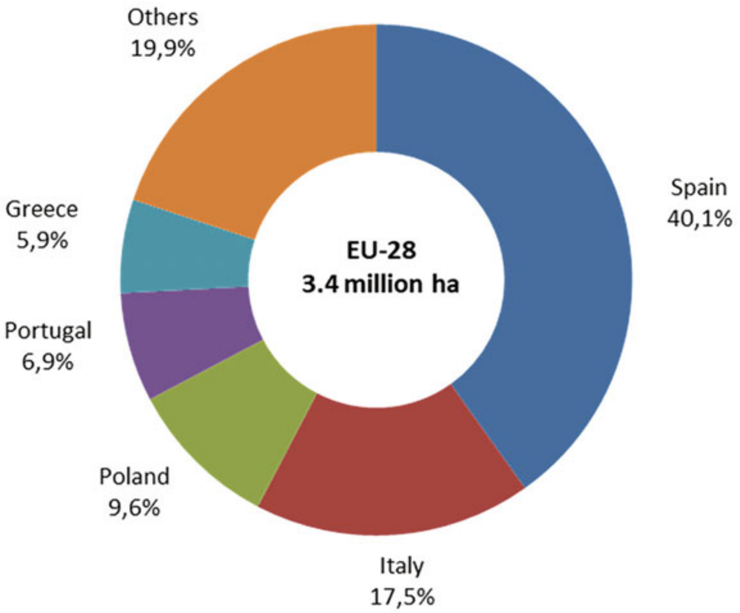


Fig. 13.16 Area of fruit by main producing EU member state, 2017 (% of EU-28)

The countries with the largest area dedicated to fruit cultivation are Spain, Italy and Poland, with a 40.1, 17.5 and 9.6% of the EU's area, respectively. Almond is the crop that occupies a larger area with 743,000 in 2017, which represents 22.5% of the EU fruit area. Of this area, 85.2% were in Spain (the world's third-largest almond producer after the USA and Australia).

According to FAOSTAT dates in 2017, the total area under the cultivation of almond trees was 1,925,887 hectares, with Spain being the country with the highest area devoted to the cultivation of almonds with 633,562 hectares, followed by the USA with 404,686 hectares.

In Spain, almond production is mainly concentrated in the Communities of Mediterranean coast: Andalusia, Murcia, Valencian Community, Aragon, Balearic Islands (Mallorca) and Catalonia. More than 81% of the area cultivated with almond in Spain is under rainfed conditions (MAPA 2019), what causes that the Spanish production has historically significantly fluctuated. Currently, the high prices paid for almonds are increasing the surface devoted to almond crops in Spain (USDA 2017). These new plantations are being established with deficit irrigation systems and using new varieties, which allows obtaining higher yields (Arquero 2013; Gutiérrez et al. 2019).

The second most common fruit crop is apple, grown in all states of the EU, with a total of 15.5% of the total fruit area in the region. Poland concentrates almost a third (31.1%) of the apple orchards in the EU. In this state, half of its total fruit area

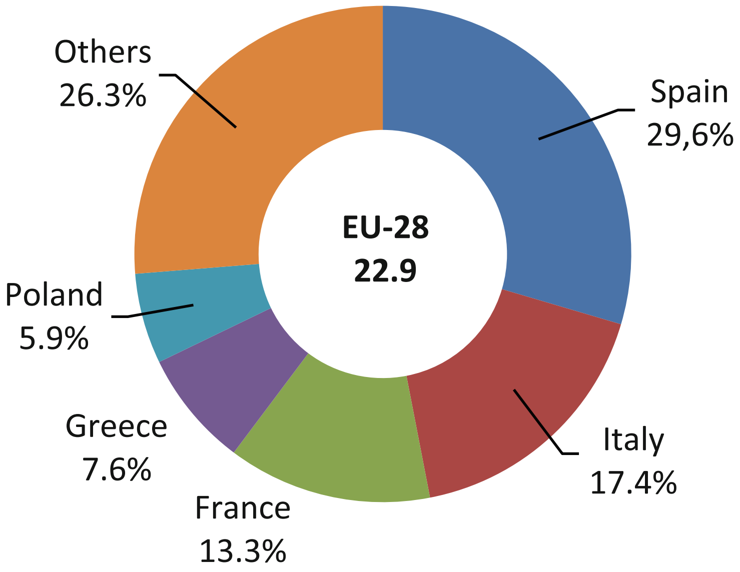


Fig. 13.17 Percentage distribution of fruit production value by primary producing member countries of EU-28 during 2017

(50.2%) is under apple cultivation. The total value of EU fruit production was 22.9 billion euros in 2017 (Fig. 13.17).

In 2017, approximately 4.59 million ha concentrated in the Mediterranean area were keen to olive cultivation in the EU. More than 75% of the total area in the European region dedicated to olive groves are in Spain (55%) and Italy (23%), followed by Greece (15%) and Portugal (7%). The rest of the member states with olive production (France, Croatia, Cyprus and Slovenia) represent a tiny percentage of the total (together they reach around 1%). Olive trees are known for their longevity. Most of the olives planted in the EU is quite old since the total area with at least 50 years old that represents about 2.5 million ha, and almost 1.7 million ha with olives between 12 and 49 years. And new olive plantations represent a minority since only 281,000 ha with trees with 5 and 11 years old, and 176,000 ha with less than 5 years old (EUROSTAT 2019b).

The EU produces two-thirds of the world's olive oil production, and 95% of the world’s olive trees are concentrated in the Mediterranean region. In general, world oil production is concentrated in southern Europe, northern Africa and the Near East (EUROSTAT 2019c).

On the other hand, in 2015, 3.2 million ha of vineyards divided into 2.4 million farms were cultivated in the EU. The member states with the most substantial areas dedicated to wine grapes in 2015 were: Spain (30% of the total EU area), France (25%), Italy (19%), Portugal (6%), Romania (6%) and Greece and Germany (3% each) (EUROSTAT 2017). Of all these vineyards, approximately 2.5 million ha were dedicated to the production of grapes with protected designation of origin (83%) or protected geographical indication (17%); a 67% of this area were in Spain and France in 2015 (EUROSTAT 2017).

13.7 Soil-Management Strategies in Rainfed Woody Crops

Almond trees, olive trees and vineyards are typical crops of the Mediterranean region, which are well adapted to the rainfall regime characteristic of the area usually grown on hillslopes of marginal lands, thus leading to increased soil erosion particularly during intense rainstorms (Martínez Raya et al. 2006; García-Ruiz 2010).

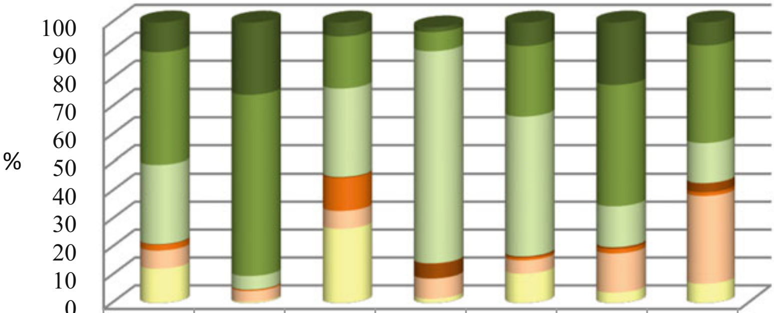
In rainfed woody crops, the soil under the trees is usually maintained bare eliminating plant cover, with mechanical (tillage) or chemical weeding (no-tillage). According to Maetens et al. (2012a) vineyards and fruit tree crops that maintain the soil bare have highest mean annual runoff coefficient (5–10%), and soil loss (10–20 Mg ha^{-1} $year^{-1}$) of land uses in Europe and Mediterranean. There are alternative systems to traditional tillage and chemical control of weeds in these crops, which allow reducing erosion and the environmental impact of agricultural activity such as reduced or minimum tillage (Martínez-Mena et al. 2013; García-Franco et al. 2015), straw and pruning mulching (Blavet et al. 2009; Prosdocimi et al. 2016; Burg et al. 2018; Cerdà et al. 2018b), grass cover (Blavet et al. 2009; Novara et al. 2011; Biddoccu et al. 2016), cover crops (Durán Zuazo et al. 2009; Ramos et al. 2010; Ruiz-Colmenero et al. 2013; Palese et al. 2014; Gómez et al. 2018) and rock fragments (Blavet et al. 2009).

Figure 13.18 presents the central soil-management systems used for fruit trees in Spain in 2017 (MAPA 2018). Figure 13.19 shows the environmental benefits of using cover crops in agricultural soils (van Es and Magdoff 2009).

13.7.1 Olive

The olive tree has great socio-economic importance in the Mediterranean area, being the representative tree of the region and significant piece of the environment and culture since Roman times (Loumou and Giourga 2003; Sofo et al. 2008). This massive extension of the surface olive orchard can be explained, among other reasons, by its rusticity, and its ability to grow where other crops cannot (sloping land and shallow soils). Although in recent years the area of irrigated olive groves has increased, most of the olive trees in the Mediterranean basin are still rainfed. In this context, in Spain, only 33% of the area cultivated with olive trees (2.55 million ha) is irrigated (MAPA 2019).

As shown in Fig. 13.20, the rainfed olive orchards in the Mediterranean basin have been traditionally cultivated in hilly areas with thick planting frames, using pruning to limit canopy size and reduce evapotranspiration and weed elimination by tillage and/or herbicide usage (Abazi et al. 2013). The combination of a large percentage of bare soil and high-intensity erosive events characteristic of the



	Olive	Vineyard	Citrus	Seed fruit	Stone fruit trees	Other fruit trees	Other woody crops
■ Traditional Tillage	10.60	25.69	4.97	1.66	8.35	22.23	8.24
■ Minumun Tillage	39.98	64.51	18.52	6.79	25.09	43.08	34.71
■ Spontaneus plant cover	28.29	4.88	31.32	75.54	49.72	14.61	14.09
■ Seeded plant cover	0.25	0.17	0.35	5.44	0.55	0.65	3.29
■ Inert cover	2.06	0.31	11.81	0.01	0.90	1.61	1.32
■ Without maintenance	6.53	3.94	6.39	7.24	4.77	14.04	31.45
■ No Tillage	12.27	0.40	26.59	1.53	10.52	3.73	6.90

Fig. 13.18 Soil-management systems in Spain (2017)

Mediterranean climate has resulted in high erosion rates in many olive growing areas, particularly on sloping areas (Gómez et al. 2008), being high erosion rates one of the leading environmental problems of this crop (Beaufoy 2001). Many studies prove the benefits of the use of CA techniques in soil conservation in olive groves. Table 13.8 shows a summary of studies published in recent years, which compare different soil-management strategies in an olive orchard in the Mediterranean region.

13.7.2 Almond

The rainfed and traditional almond cultivation in the Mediterranean semi-arid regions has been characterized by low-density plantations (~200 trees ha^{-1}), weed control by tillage and located in mountainous areas (Fig. 13.21). These features explain why almond orchards are related to severe soil erosion (Martínez Raya et al. 2006; Durán Zuazo et al. 2008). Nevertheless, erosion problems have been accentuated in the last time by land use changes favoured by the subsidy policy from the EU. In this sense, Faulkner (1995) pointed out how large areas occupied by Mediterranean shrubs have been replaced with almond trees, usually on steep slopes. In Murcia, a region of SE Spain, Romero Díaz et al. (2012) demonstrated how there is a clear relationship between the EU subsidy policy and the increase in the area dedicated to the cultivation of almond trees.

In certain regions such as Andalusia (S Spain), most of the mountain almond orchards are located in areas where traditionally unable to work with other crops, and

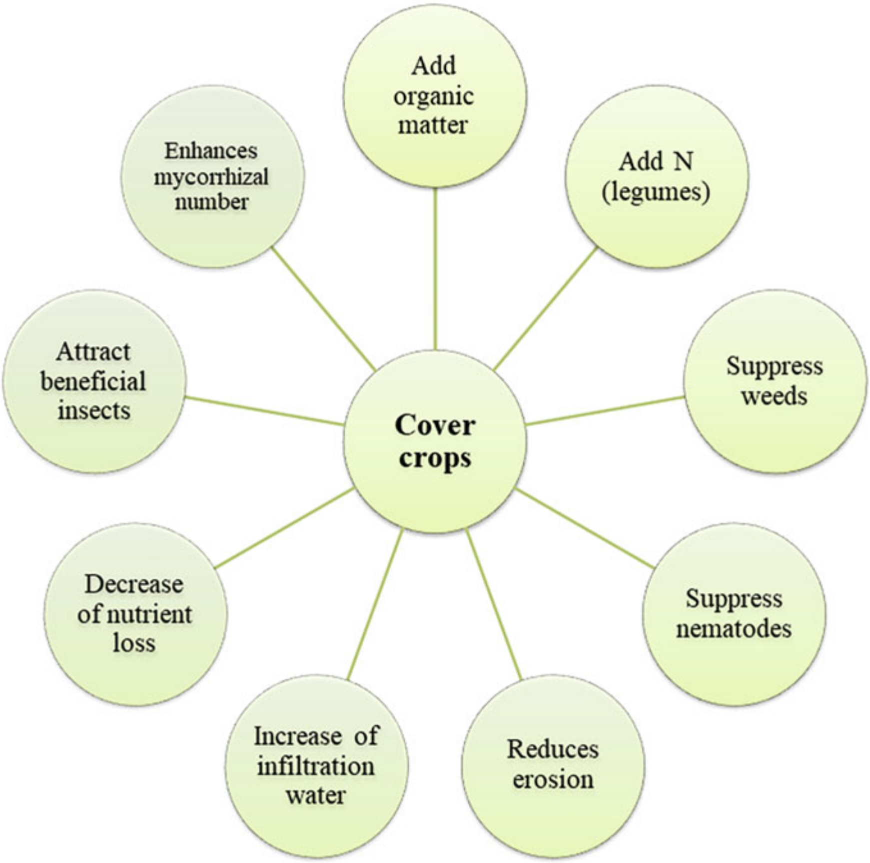


Fig. 13.19 Benefits of cover crops

Fig. 13.20 Traditional rainfed hillslope olive plantations in Córdoba (**a**) and Jáen (**b**) provinces in Andalusia (*S* Spain)

Table 13.8 Soil-management strategies in rainfed hillslope olive plantations

Soil-management strategy	Impact on soil /soil erosion and runoff rates	Reference
Conventional tillage (CT)/cover crops: seeded homogeneous grass (GC), seeded mix (MC seeded) and non-seeded cover by vegetation natural (MC natural)	Reduction in soil loss: 46.7 in CT to 6.5 and 7.9 t ha^{-1} $year^{-1}$ in GC and MC seeded, respectively. The increasing diversity of plant species and arthropods	Gómez et al. (2018)
Tillage (T)/cover crops: legumes (LEG), barley (HOR) and Brachypodium (BRA)	Tillage had the highest erosion rate: 6.8 t ha^{-1} $year^{-1}$ and cover crops decreased erosion rates: LEG, 41; HOR, 60 and BRA, 80% respect to T	Sastre et al. (2017)
Tillage/cover crops	Preserve biological soil fertility	Turrini et al. (2017)
Conventional/cover crops/organic amendment	Greater carbon sequestration	Vicente-Vicente et al. (2017)
Tillage/cover crops	The tilled micro-plots showed a surface runoff three times higher than the covered micro-plots. Soil losses differ markedly between both treatments, being non-existent in GC plots	Palese et al. (2015)
Tillage/no tillage/cover crops	Improvements in soil quality and biodiversity conservation	Sánchez-Moreno et al. (2015)
Tillage/cover crops	Increased water retention capacity	Palese et al. (2014)
Tillage/no-till with cover (crops and pruning residues)	Greater microbiological diversity	Sofo et al. (2014)
Shallow tillage/mechanical mowing	Improvements in SOC and biological activity	Soriano et al. (2014)
Tillage/cover crops: sown and spontaneous	Water loss by runoff was reduced with the use of cover crop in six of the eight fields, with an average of 22%. The reduction of soil losses was registered in all plots and a higher percentage, with an average of 76%	Espejo-Pérez et al. (2013)
Tillage (T)/no-till + herbicide (NTH)/ No-till + no herbicide (NT)	NT showed the lowest soil loss (29.3 kg ha^{-1} $year^{-1}$) and runoff coefficient (0.8%). NTH showed an intermediate behaviour (soil loss: 113.1 kg ha^{-1} $year^{-1}$; runoff coefficient: 2.1%). And T was the treatment with the highest soil loss, 2617 kg ha^{-1} $year^{-1}$ and runoff coefficient of 5%	Kairis et al. (2013)

(continued)

Table 13.8 (continued)

Soil-management strategy	Impact on soil /soil erosion and runoff rates	Reference
Tillage/cover crops	Improved soil physicochemical properties	Gucci et al. (2012)
Tillage/cover crops	Augmentation of SOC	Nieto et al. (2013)
Tillage/cover crops	Increased water retention capacity	Celano et al. (2011)
No-tillage (NT)/no-tillage with barley strips (BS)/no-tillage with native vegetation strips of 4 m width (NVS)	The highest erosion and runoff rates were measured under NT, with a mean of 17.3 t ha^{-1} $year^{-1}$ and 140.0 mm $year^{-1}$, respectively. The BS and NVS concerning the NT reduced runoff by 95 and 94% and erosion by 71 and 59%, respectively	Durán Zuazo et al. (2009)
Conventional tillage (CT) / Cover crops (CC)	Cover crops decreased soil erosion and runoff. Soil loss was 1.94 and 0.04 kg m^{-2} $year^{-1}$, in CT and CC, respectively. Runoff was 91.9 and 32.7 mm, in CT and CC, respectively. Reduction of nutrient loss in sediments and runoff	Gómez et al. (2009)
Non-tillage with barley strips (BS)/ conventional tillage (CT)/non-tillage without plant strips (NT)	Cover crops decreased soil erosion and runoff. BS and CT reduced erosion by 92 and 78%, to the NT and runoff by 49 and 72%, respectively. The total NPK losses from BS averaged 0.87, 0.07 and 0.72 kg ha^{-1}, from CT 1.82, 0.11 and 0.97 kg ha^{-1} and from NT 3.15, 0.29 and 2.45 kg ha^{-1}, respectively	Francia Martínez et al. (2006)

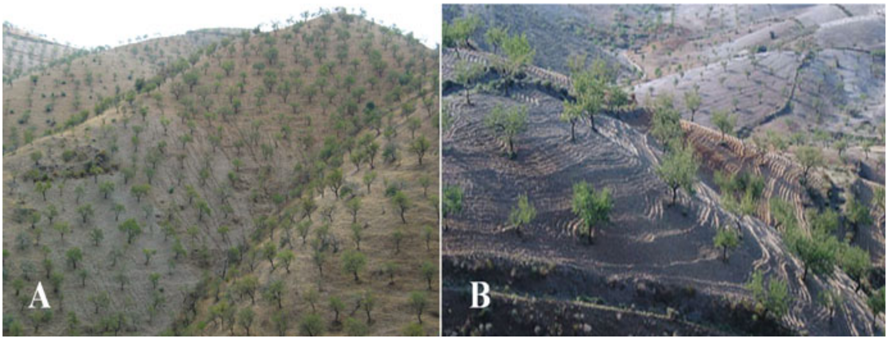


Fig. 13.21 Traditional rainfed hillslope almond plantations (**a**) and conventional contour tillage (**b**) in Granada province in Andalusia (*S* Spain)

that have very few economic alternatives; therefore the almond tree plays a strategic role in income for farmers, and in fixing the population in the rural environment (Kallas et al. 2006). Further, from an environmental perspective, the contributions of almond orchards in these areas are significantly relevant.

Arquero (2013) reported rainfed almond yield between 350 and 400 kg ha^{-1}, with high environmental cost due to conventional tillage that provoked high water losses by soil evaporation, depletion of SOM and plant nutrients, and soil erosion (Martínez-Mena et al. 2008). Table 13.9 displays different studies in the Mediterranean to soil-management used for almond cultivation.

13.7.3 Vineyard

Viticulture is a vital agro-economic activity in the Mediterranean region. According to the data from the International Organisation of Vine and Wine, there was just over 7.4 million ha of vineyards worldwide in 2018 (OIV 2019), of which 39% are in Mediterranean countries (Spain 13%; France 11%; Italy 9% and Turkey 6%). In the traditionally managed vineyard, in the Mediterranean region, the soil is tilled several times a year to avoid competition for nutrients and water with weeds. Vineyards are one of the lands uses of the Mediterranean region where there are higher erosion rates. According to Kosmas et al. (1997), the highest erosion rates in agricultural lands of the Mediterranean region are registered in vineyards in hilly areas (average soil loss of 1.4 Mg ha^{-1} $year^{-1}$). Vineyards are a very intensively managed agroecosystem with numerous pesticide applications, soil tillage operations and high landscape simplification (Nicholls et al. 2008), which generates substantial environmental impacts. Several authors have evidenced how soil degradation in vineyards has increased during the past decades, as a result of practices such as the application of herbicides, intensive tillage or the use of heavy machinery (Ramos and Martínez-Casasnovas 2007; Novara et al. 2011; Arnáez et al. 2012; Zaller et al. 2018).

The reasons that explain the high rates of erosion in the vineyards are diverse. Firstly, the ground is almost bare for much of the year. The plants are leafless from November to April, and in May they begin to develop the foliage. In summer, when the plant has reached maximum development, the rows remain unprotected (Fig. 13.22). In the Mediterranean climate, more intense rainfall occurs in autumn and spring, when the soil is almost bare (García-Ruiz 2010). The plant cover decreases in the new vineyard plantations that together with the disturbance caused in the soil after planting produced high erosion rates during the first two years (Rodrigo-Comino et al. 2018b). Secondly, the vines are usually planted on sloping terrain, which increases the risk of erosion. And finally, the Mediterranean vineyards are located in very erodible soils, with a weak structure due to the low content of nutrients and organic matter (Novara et al. 2011; Muñoz-Rojas et al. 2013).

In many Mediterranean regions, vineyards have been cultivated on hillslopes with terracing systems utilizing stone walls. Intensification of viticulture, due to the increase of the related economic market, has been based on new terracing systems

Table 13.9 Soil-management strategies in rainfed hillslope almond plantations

Soil-management strategy	Impact on soil/soil erosion and runoff rates	Reference
Conventional tillage, no-tillage, green manure and compost	Ecosystem services can be improved through agroecological practices: nutrient cycling, carbon stock, habitat provisioning and food provisioning, but not pest control and pollination	De Leijster et al. (2019)
Conventional tillage (CT), reduced tillage (RT) and reduced tillage + green manure (RTG)	The CT increased total runoff and soil loss three times as compared to RT and RTG. Higher SOC contents and aggregate stability were observed under reduced tillage with green manure	Almagro et al. (2016)
Conventional tillage – No-tillage + Herbicides – No-tillage + Sowing – No-tillage + Green manure	Soil management that reduces soil alteration and increases biomass contributions as cover crops have improved the physicochemical, hydrological and biological properties of the soil	Cucci et al. (2016)
Conventional tillage, No-tillage + preemergence herbicides, No-tillage + foliar herbicides, No-tillage + sowing and No-tillage + green manure	The control of post-emergency weeds by harvest or using chemical herbicides or the green manure of the cover crop are useful tools to limit the impact on the soil and favour the growth and diversity of the flora	Fracchiolla et al. (2016)
No-tillage, reduced tillage, reduced tillage + green manure	The practice that proved most effective in the sequestration of SOC was reduced tillage combined with the application of green manure	García-Franco et al. (2015)
Tillage and no-tillage	No-tillage improved soil physical properties and soil quality	Castellini et al. (2013)
No-tillage, reduced tillage, reduced tillage + green manure	Reduced tillage treatments registered crop yield and N-foliar content than the no-tillage treatment. In soils prone to compaction, it is necessary to perform some tillage to maintain productivity	Martínez-Mena et al. (2013)
Mineral fertilization – organic fertilization	The organic fertilization had positive effects on soil microbiological and physicochemical properties, such as to increase the availability of soil nutrients, favour microbial activity and improve soil structure	Macci et al. (2012)
Conventional tillage (CT), No-tillage + aromatic shrub: thyme strips (THS), rosemary strips (ROS) and sage strips (SAS)	Reduction of soil loss: THS, 93%, ROS, 91% and SAS, 69% respect to CT. Reduction of runoff: THS, 80%, ROS, 82% and SAS, 51% respect to CT	Durán Zuazo et al. (2008)
Tillage – cover crops	In semi-arid environments, the use of cover crops allows improving soil quality, by increasing the SOM stock, improving the fertility of the soil and enhancing biological activity	Ramos et al. (2010)

(continued)

Table 13.9 (continued)

Soil-management strategy	Impact on soil/soil erosion and runoff rates	Reference
Bare soil and cover crops [Thyme (T), barley (B) and lentils (L)]	Reduction of soil loss respect to bare soil: T, 97%; B, 87% and L, 58%. Reduction of runoff respect to bare soil: T, 91%; B, 59% and L, 18%	Martínez Raya et al. (2006)

Fig. 13.22 Hillslope vineyard plantations without plant cover (**a**) and terraced with plant strips (**b**)

constructed using heavy machinery and resulting in high negative environmental and landscape impacts (Cots-Folch et al. 2006). In this line, García-Ruiz (2010) showed how the expansion of vineyards to steep slopes with the use of unstable bench terraces means an increase in erosion. Historically, in some regions, winemakers have taken traditional protective measures to reduce soil erosion, such as the construction of streams, to channel surface flow and small stone walls to minimize soil loss, which has been shown as ineffective in preventing land degradation (Rodrigo Comino et al. 2016). Table 13.10 shows the most relevant studies for Mediterranean vineyards in relation to soil-management strategies used for mitigating erosion process.

13.8 Conclusions

Mediterranean land degradation by water erosion in agricultural areas is one of the most critical environmental troubles expected to be aggravated by global warming and climate change. The soil erosion adversely impacts on crop yield because it reduces soil-water infiltration capacity, soil-water availability, drainage capacity, plant rooting depth, soil biodiversity and availability of plant nutrients. The Mediterranean basin is a traditional area for rainfed fruit crops such as olive, almond and vineyard, which represent an important agricultural production sector. Most of these crops are cultivated on marginal lands with poor agricultural aptitude, on sloping,

Table 13.10 Soil-management strategies in rainfed hillslope vineyard plantations

Soil–management strategy	Impact on soil /soil erosion and runoff rates	References
Conventional and grass cover	Reduction of soil erosion (43.7–14.6 Mg ha^{-1} year^{-1}) with grass cover	Pappalardo et al. 2019
Tillage and cover crops	Reduction of soil erosion: 222.61–43.97 kg ha^{-1}, in plots with rows along the contour lines and 1187.31–254.32 kg ha^{-1}, in plots with rows up-and-down the slope. Reduction of runoff coefficient: 1.8 to 1.2% in plots with rows along the contour lines and 16 to 8.3, in plots with rows along the slope	Bagagiolo et al. (2018)
Cover crop + no-tillage (S+NT), Cover crop + tillage (S+T) and No vegetation and tillage (UV)	Organic C and N pools and microbial biomass/activity in S+NT were higher than S+T, while UV showed intermediate values. S+NT exhibited higher particulate organic matter C in soil	Belmonte et al. (2018)
Conventional tillage (T), Brachypodium cover (CB) and Spontaneous vegetation (CS)	CS was the most effective to reduce runoff and nitrogen loss by producing three times less runoff than T and 6 times less nitrate loss. T resulted in higher nitrogen loss with more runoff and higher runoff nitrate concentrations	García-Díaz et al. (2017)
Tillage (T) and Grass cover (GC)	Reduction of soil loss: T, 7.0 and GC 1.8 Mg ha^{-1} year^{-1} and runoff coefficient: T, 11.8 and GC, 8.7%. Reduction of nitrogen and potassium loss	Biddoccu et al. (2016)
Tillage, no-tillage and cover crops	Cover crops enhance infiltration rates through increase soil porosity, also reduce soil compaction and superficial crusting	Linares et al. (2014)
Tillage and cover crops	The cover crop improved the soil quality by enhancing various physical, chemical and biological soil properties	López-Piñeiro et al. (2013)
Tillage (T), *Brachypodium* Cover (CB) and *Secale* cover (CS)	Reduction of soil erosion: T, 5.88; CB, 0.78 and CS, 1.27 t ha^{-1} year^{-1}. Increase infiltration, aggregate stability and soil organic carbon	Ruiz-Colmenero et al. (2013)
Tillage (T), cover crops: Brachypodium (B), Spontaneous vegetation (SV), Secale (S) and Hordeum (H)	Reduction of soil erosion: T, 0.4–1.8; B, 0.02–0.3; SV, 0.24; S, 0.15 and H, 0.32 t ha^{-1} year^{-1}. Reduction of runoff coefficient: T, 0.44–1137; B, 0.30–1.76; SV, 0.34; S, 1.10 and H, 2.65%	Bienes et al. (2012)
Tillage (T) and grass cover (GC)		

(continued)

Table 13.10 (continued)

Soil–management strategy	Impact on soil /soil erosion and runoff rates	References
	Reduction of runoff: T, 943.6 and GC, 654.0 mm. Reduction of soil loss: T, 113.8 Mg ha^{-1} and GC, 26.5 Mg ha^{-1}. Improves the structure of the soil, which allows increasing the infiltration of water. Also, the stock of organic N is increased	Corti et al. (2011)
Tillage and cover crops: *Vicia faba* (VF), *V. faba* + *Vicia sativa* (VV), *Trifolium subterraneum+Festuca rubra+Lolium perenne* (TFL), *T. subterraneum* + *F. rubra* + *Festuca ovina* (TFF); *Triticum durum* (T) and *T. durum* + *V. sativa* (TV)	Cover crops reduce soil erosion compared to tillage: TFF, 76%; VV, 74.94%; TFL, 66.2%, TD, 56%; TV, 69.8 and VF, 39.6%	Novara et al. (2011)
Tillage and Cover crops	The use of cover crops reduced soil erosion by an average of 68%, ranging from 34 to 93%. The reduction in the runoff coefficient was not as significant, with an average of 5% for tilled soils, 0.9% for permanent covers and 1.4% for cut covers. Also increasing the soil organic matter and reducing the loss of nutrients	Ruiz-Colmenero et al. (2011)

rocky or shallow soils, and therefore highly susceptible to water erosion. Hence, some important considerations should be comprised to attain sustainable SWC strategies in this region. First, it has been shown that conventional hillslope agriculture is not tenable in the long term, degrading the soil and reducing its productive ability, as is the case in traditional rainfed fruit crops, where high rates of erosion and runoff are recorded. In this regard redesigning conventional operations will be crucial in making more sustainable intensification of hillslope farming. Secondly, CA techniques could be an essential alternative tool to ensure a better balance in the ecosystem services supplied by the soil and to guarantee the sustainability and productivity of agroecosystems in this type of environment. That is, the implementation of soil conservation practices is one of the mechanisms to adaptation and mitigation climate change while obtaining environmental, social and economic benefits.

Finally, agricultural development is currently facing extraordinary challenges and not less critical how to meet them, in which the sustainable intensification performs a significant role, depending on the integrated use of a wide range of conservation strategies to manage soil and water in hillslopes. Thus, farmers should be fostered to adapt to changing conditions by preserving natural resources, and that involve improvements in soil functions and soil-water availability for rainfed fruit crops.

13.9 Future Perspectives

Soil loss due to water erosion in agricultural areas is one of the most serious threats to the environment in the Mediterranean region, and is expected to be exacerbated by the effects of climate change. Therefore, the adoption of agricultural conservation practices that reduce runoff and soil losses are essential to guarantee the economic and environmental sustainability of Mediterranean agroecosystems.

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References

Abazi U, Lorite IJ, Cárceles B, Martínez Raya A, Durán ZVH, Francia JR, Gómez JA (2013) WABOL: a conceptual water balance model for analyzing rainfall water use in olive orchards under different soil and cover crop management strategies. Comput Electron Agric 91:35–48. https://doi.org/10.1016/j.compag.2012.11.010

Abid M, Lal R (2009) Tillage and drainage impact on soil quality: II. Tensile strength of aggregates, moisture retention and water infiltration. Soil Tillage Res 103(2):364–372. https://doi.org/10.1016/j.still.2008.11.004

Adhikari K, Hartemink AE (2016) Linking soils to ecosystem services - a global review. Geoderma 262:101–111. https://doi.org/10.1016/j.geoderma.2015.08.009

Aguilera E, Lassaletta L, Gattinger A, Gimeno BS (2013) Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agric Ecosyst Environ 168:25–36. https://doi.org/10.1016/j.agee.2013.02.003

Almagro M, de Vente J, Boix-Fayos C, García-Franco N, Melgares de Aguilar J, González D, Solé-Benet A, Martínez-Mena M (2016) Sustainable land management practices as providers of several ecosystem services under rainfed Mediterranean agroecosystems. Mitig Adapt Strateg Glob Chang 21(7):1029–1043. https://doi.org/10.1007/s11027-013-9535-2

Amézketa E (1999) Soil aggregate stability: a review. J Sustain Agric 142(2):83–151. https://doi.org/10.1300/J064v14n02_08

Arnáez J, Ruiz-Flaño P, Lasanta T, Ortigosa L, Llorente JA, Pascual N, Lana-Renault N (2012) Efectos de las rodadas de tractores en la escorrentía y erosión de suelos en laderas cultivadas con viñedos. Cuad Investig Geogr 38(1):115–120. https://doi.org/10.18172/cig.1278

Arquero O (2013) Manual del almendro. Junta de Andalucía Consejería de Agricultura, Pesca y Desarrollo Rural, Sevilla

Azooz RH, Arshad MA (1996) Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Can J Soil Sci 76(2):143–152. https://doi.org/10.4141/cjss96-021

Bagagiolo G, Biddoccu M, Rabino D, Cavallo E (2018) Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. Environ Res 166:690–704. https://doi.org/10.1016/j.envres.2018.06.048

Bakker MM, Govers G, Jones RA, Rounsevell MDA (2007) The effect of soil erosion on Europe's crop yields. Ecosystems 10(7):1209–1219. https://doi.org/10.1007/s10021-007-9090-3

Balesdent J, Chenu C, Balabane M (2000) Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res 53(3–4):215–230. https://doi.org/10.1016/S0167-1987(99)00107-5

Barrios E (2007) Soil biota, ecosystem services and land productivity. Ecol Econ 64(2):269–285. https://doi.org/10.1016/j.ecolecon.2007.03.004

Beaufoy G (2001) EU policies for olive farming. Unsustainable on all counts. BirdLife International-WWF, Brussels

Belmonte SA, Celi L, Stahel RJ, Bonifacio E, Novello V, Zanini E, Steenwerth KL (2018) Effect of long-term soil management on the mutual interaction among soil organic matter, microbial activity and aggregate stability in a vineyard. Pedosphere 28(2):288–298. https://doi.org/10.1016/S1002-0160(18)60015-3

Bertrand M, Barot S, Blouin M, Whalen J, de Oliveira T, Roger-Estrade J (2015) Earthworm services for cropping systems. A review. Agron Sustain Dev 35(2):553–567. https://doi.org/10.1007/s13593-014-0269-7

Biddoccu M, Ferraris S, Opsi F, Cavallo E (2016) Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North-West Italy). Soil Tillage Res 155:176–189. https://doi.org/10.1016/j.still.2015.07.005

Bienes R, Marqués MJ, Ruíz-Colmenero M (2012) Cultivos herbáceos, viñedos y olivares. el manejo tradicional del suelo y sus consecuencias en la erosión hídrica. Cuad Investig Geogr 38(1):49–74. https://doi.org/10.18172/cig.1275

Bienes R, Marques MJ, Sastre B, García-Díaz A, Ruiz-Colmenero M (2016) Eleven years after shrub revegetation in semiarid eroded soils. Influence in soil properties. Geoderma 273:106–114. https://doi.org/10.1016/j.geoderma.2016.03.023

Blavet D, De Noni G, Le Bissonnais Y, Leonard M, Maillo L, Laurent JY et al (2009) Effect of land use and management on the early stages of soil water erosion in French Mediterranean vineyards. Soil Tillage Res 106(1):124–136. https://doi.org/10.1016/j.still.2009.04.010

Boardman J, Vandaele K, Evans R, Foster IDL (2019) Off-site impacts of soil erosion and runoff: why connectivity is more important than erosion rates. Soil Use Manag 35(2):245–256. https://doi.org/10.1111/sum.12496

Borrelli P, Robinson DA, Fleischer LR, Lugato E, Ballabio C, Alewell C et al (2017) An assessment of the global impact of 21st century land use change on soil erosion. Nat Commun 8:2013. https://doi.org/10.1038/s41467-017-02142-7

Bravo CA, Giráldez JV, Ordóñez R, González P, Torres FP (2007) Long-term influence of conservation tillage on chemical properties of surface horizon and legume crops yield in a vertisol of Southern Spain. Soil Sci 172(2):141–148. https://doi.org/10.1097/ss.0b013e31802db198

Burg P, Masan V, Cizkova A, Visacki V (2018) Evaluation of impact of cover materials on reduction of water erosion of soil in vineyards. Eng Rural Dev 17:658–664. https://doi.org/10.22616/ERDev2018.17.N312

Capowiez Y, Sammartino S, Michel E (2014) Burrow systems of endogeic earthworms: effects of earthworm abundance and consequences for soil water infiltration. Pedobiologia 57(4–6):303–309. https://doi.org/10.1016/j.pedobi.2014.04.001

Caron P, Biénabe E, Hainzelin E (2014) Making transition towards ecological intensification of agriculture a reality: the gaps in and the role of scientific knowledge. Curr Opin Environ Sustain 8:44–52. https://doi.org/10.1016/j.cosust.2014.08.004

Castellini M, Pirastru M, Niedda M, Ventrella D (2013) Comparing physical quality of tilled and no-tilled soils in an almond orchard in southern Italy. Ital J Agron 8(3):149–157. https://doi.org/10.4081/ija.2013.e20

Celano G, Palese AM, Ciucci A, Martorella E, Vignozzi N, Xiloyannis C (2011) Evaluation of soil water content in tilled and cover-cropped olive orchards by the geoelectrical technique. Geoderma 163(3–4):163–170. https://doi.org/10.1016/j.geoderma.2011.03.012

Cerdà A, Rodrigo-Comino J, Giménez-Morera A, Keesstra SD (2017) An economic, perception and biophysical approach to the use of oat straw as mulch in Mediterranean rainfed agriculture land. Ecol Eng 108(October):162–171. https://doi.org/10.1016/j.ecoleng.2017.08.028

Cerdà A, Rodrigo-Comino J, Novara A, Brevik EC, Vaezi AR, Pulido M, Giménez-Morera A, Keesstra SD (2018a) Long-term impact of rainfed agricultural land abandonment on soil erosion in the Western Mediterranean basin. Prog Phys Geogr 42(2):202–219. https://doi.org/10.1177/0309133318758521

Cerdà A, Rodrigo-Comino J, Giménez-Morera A, Novara A, Pulido M, Kapović-Solomun M, Keesstra SD (2018b) Policies can help to apply successful strategies to control soil and water losses. The case of chipped pruned branches (CPB) in Mediterranean citrus plantations. Land Use Policy 75:734–745. https://doi.org/10.1016/j.landusepol.2017.12.052

Cherlet M, Ivits E, Sommer S, Tóth G, Jones A, Montanarella L, Belward A (2013) Land productivity dynamics in europe towards a valuation of land degradation in the. EU 719 (1):383–425. https://doi.org/10.2788/70673

Cooper SD, Lake PS, Sabater S, Melack JM, Sabo JL (2013) The effects of land use changes on streams and rivers in mediterranean climates. Hydrobiologia 719(1):383–425. https://doi.org/10.1007/s10750-012-1333-4

Corti G, Cavallo E, Cocco S, Biddoccu M, Brecciaroli G, Agnelli A (2011) Evaluation of erosion intensity and some of its consequences in vineyards from two hilly environments under a Mediterranean type of climate, Italy. Soil Eros. Issues Agric. https://doi.org/10.5772/25130

Cots-Folch R, Martínez-Casasnovas JA, Ramos MC (2006) Land terracing for new vineyard plantations in the north-eastern Spanish Mediterranean region: Landscape effects of the EU Council Regulation policy for vineyards' restructuring. Agric Ecosyst Environ 115(1–4):88–96. https://doi.org/10.1016/j.agee.2005.11.030

Coyle C, Creamer RE, Schulte RPO, O'Sullivan L, Jordan P (2016) A functional land management conceptual framework under soil drainage and land use scenarios. Environ Sci Pol 56:39–48. https://doi.org/10.1016/j.envsci.2015.10.012

Cucci G, Lacolla G, Crecchio C, Pascazio S, Giorgio DDE (2016) Impact of long term soil management practices on the fertility and weed flora of an almond orchard. Turk J Agric For 40:194–202. https://doi.org/10.3906/tar-1502-87

De Alba S, Benito G, Pérez-González A (1998) Erosion de suelo en episodios de lluvia de elevada intensidad. In: Gómez-Ortiz AGA, Salvador F, Schulte L (eds.) Investig. recientes la Geomorfol. española. Barcelona, pp 483–492

De Leijster V, João M, Wassen MJ, Ramos-font ME, Belén A, Díaz M, Staal M, Verweij PA (2019) Agroecological management improves ecosystem services in almond orchards within one year. Ecosyst Serv 38:100948. https://doi.org/10.1016/j.ecoser.2019.100948

Diodato N, Bellocchi G, Romano N, Chirico GB (2011) How the aggressiveness of rainfalls in the Mediterranean lands is enhanced by climate change. Clim Chang 108:591. https://doi.org/10.1007/s10584-011-0216-4

Dupas R, Delmas M, Dorioz JM, Garnier J, Moatar F, Gascuel-Odoux C (2015) Assessing the impact of agricultural pressures on N and P loads and eutrophication risk. Ecol Indic 48:396–407. https://doi.org/10.1016/j.ecolind.2014.08.007

Durán Zuazo VH, Rodríguez Pleguezuelo CR (2008) Soil-erosion and runoff prevention by plant covers. A review. Agron Sustain Dev 28:65–86. https://doi.org/10.1051/agro

Durán Zuazo VH, Rodríguez Pleguezuelo CR, Francia Martínez JR, Martínez Raya A, Arroyo Panadero L, Cárceles Rodríguez B, Navarro Moll MC (2008) Benefits of plant strips for sustainable mountain agriculture. Agron Sustain Dev 28(4):497–505. https://doi.org/10.1051/agro:2008020

Durán Zuazo VH, Rodríguez Pleguezuelo CR, Arroyo Panadero L, Martínez Raya A, Francia Martínez JR, Cárceles Rodríguez B (2009) Soil conservation measures in rainfed olive orchards in south-eastern Spain: Impacts of plant strips on soil water dynamics. Pedosphere 19 (4):453–464. https://doi.org/10.1016/S1002-0160(09)60138-7

Durán Zuazo VH, Rodríguez Pleguezuelo CR, Flanagan D, García Tejero IF, Muriel Fernández JL (2011) Sustainable land use and agricultural soil. Altern Farming Syst Biotechnol Drought Stress Ecol Fertil. https://doi.org/10.1007/978-94-007-0186-1_5

Durán Zuazo VH, Rodríguez Pleguezuelo CR, Cuadros Tavira S, Francia Martínez JR (2014) Linking soil organic carbon stocks to land-use types in a mediterranean agroforestry landscape. J Agric Sci Technol 16(3):667–679

Durán Zuazo VH, Rodríguez Pleguezuelo CR, Francia Martínez JR, Cuadros Tavira S, García Tejero IF (2015a) Linking semiarid-mountain agriculture to environmental benefits and adverse impact. In: Arid semi-arid environ biogeodiversity, impacts environ. challenges. https://doi.org/10.1002/9781634834100.ch1

Durán Zuazo VH, Rodríguez Pleguezuelo CR, Cárceles Rodríguez B, Melgares P, Francia JD, Martínez JR, Cuadros Tavira S, García Tejero IF (2015b) Plant strips as a sustainable strategy in reducing soil erosion in rainfed-tree crops. In: Reuter J (ed) Cover crop cultiv manag benefits. Nova Science Publishers, Hauppauge, pp 73–102

Endale DM, Potter TL, Strickland TC, Bosch DD (2017) Sediment-bound total organic carbon and total organic nitrogen losses from conventional and strip tillage cropping systems. Soil Tillage Res 171:25–34. https://doi.org/10.1016/j.still.2017.04.004

Espejo-Pérez AJ, Rodríguez-Lizana A, Ordóñez R, Giráldez JV (2013) Soil loss and runoff reduction in olive-tree dry-farming with cover crops. Soil Sci Soc Am J 77(6):2140–2148. https://doi.org/10.2136/sssaj2013.06.0250

EUROSTAT (2017) Structure of vineyards in 2015. http://ec.europa.eu/eurostat/documents/2995521/7964277/5-04042017-BP-EN.pdf/149e5e9a-4ae6-466b-baec-0273fe0c08a4

EUROSTAT (2018) Agri-environmental indicator – soil erosion. https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=254669#Assessment

EUROSTAT (2019a) The fruit and vegetable sector in the EU - a statistical overview. Available online https://ec.europa.eu/eurostat/statistics-explained/index.php?title=The_fruit_and_vegetable_sector_in_the_EU_-_a_statistical_overview#Output_values

EUROSTAT (2019b) Agricultural production - orchards. Available online https://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_orchards#Olive_trees

EUROSTAT (2019c) Agricultural production - crops. Available online https://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_crops#Olives

EUROSTAT (2020) Statistical office of the European Union. Available online https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=aei_pr_soiler&lang=en

FAO (2011) Save and grow. A policymaker's guide to the sustainable intensification of smallholder crop production. FAO Food Agric. Organ. United Nations. Rome. http://www.fao.org/policy-support/resources/resources-details/en/c/421716/

FAO (2012) Coping with water scarcity: an action framework for agriculture and food security. Food Agric Organ United Nations

FAO (2014) What is conservation agriculture. http://www.fao.org/ag/ca/1a.html

FAO (2017) The future of food and agriculture: trends and challenges. Futur food Agric trends challenges. http://www.fao.org/3/a-i6583e.pdf

FAO-ITPS (2015) Status of the world's soil resources (SWSR) - main report. FAO, Rome. http://www.fao.org/3/a-bc595e.pdf

FAOSTAT (2019) Food and agriculture organisation of the United Nations. Available http://www.fao.org/faostat/en/#data/QC

Faucon MP, Houben D, Lambers H (2017) Plant functional traits: soil and ecosystem services. Trends Plant Sci 22(2):385–394. https://doi.org/10.1016/j.tplants.2017.01.005

Faulkner H (1995) Gully erosion associated with the expansion of unterraced almond cultivation in the coastal Sierra de Lujar, S. Spain L Degrad Dev 6(3):179–200. https://doi.org/10.1002/ldr.3400060306

Ferreira IQ, Arrobas M, Claro AM, Rodrigues MA (2013) Soil management in rainfed olive orchards may result in conflicting effects on olive production and soil fertility. Span J Agric Res 2:472–480. https://doi.org/10.5424/sjar/2013112-3501

Fracchiolla M, Terzi M, Frabboni L, Caramia D, Lasorella C, De Giorgio D, Montemurro P, Cazzato E (2016) Influence of different soil management practices on ground-flora vegetation in an almond orchard. Renew Agric Food Syst 31(4):300–308. https://doi.org/10.1017/S1742170515000241

Francia Martínez JR, Durán Zuazo VH, Martínez Raya A (2006) Environmental impact from mountainous olive orchards under different soil-management systems (SE Spain). Sci Total Environ 358(1–3):46–60. https://doi.org/10.1016/j.scitotenv.2005.05.036

Friedrich T, Derpsch R, Kassam A (2012) Overview of the worldwide spread of conservation agriculture. Field Actions Sci Rep 8:3–7

Galati A, Gristina L, Crescimanno M, Barone E, Novara A (2015) Towards more efficient incentives for agri-environment measures in degraded and eroded vineyards. L Degrad Dev 26(6):557–564. https://doi.org/10.1002/ldr.2389

García Tejero IF, Durán Zuazo VH (2018) Water scarcity and sustainable agriculture in semiarid environment. Academic, Cambridge

García-Barrón L, Aguilar M, Sousa A (2011) Evolution of annual rainfall irregularity in the southwest of the Iberian Peninsula. Theor Appl Climatol 103:13–26. https://doi.org/10.1007/s00704-010-0280-0

García-Barrón L, Morales J, Sousa A (2013) Characterisation of the intra-annual rainfall and its evolution (1837-2010) in the southwest of the Iberian Peninsula. Theor Appl Climatol 114:445–457. https://doi.org/10.1007/s00704-013-0855-7

García-Díaz A, Allas RB, Gristina L, Cerdà A, Pereira P, Novara A (2016) Carbon input threshold for soil carbon budget optimization in eroding vineyards. Geoderma 271:144–149. https://doi.org/10.1016/j.geoderma.2016.02.020

García-Díaz A, Bienes R, Sastre B, Novara A, Gristina L, Cerdà A (2017) Nitrogen losses in vineyards under different types of soil groundcover. A field runoff simulator approach in central Spain. Agric Ecosyst Environ 236:256–267. https://doi.org/10.1016/j.agee.2016.12.013

García-Franco N, Albaladejo J, Almagro M, Martínez-Mena M (2015) Beneficial effects of reduced tillage and green manure on soil aggregation and stabilization of organic carbon in a Mediterranean agroecosystem. Soil Tillage Res 153:66–75. https://doi.org/10.1016/j.still.2015.05.010

García-Ruiz JM (2010) The effects of land uses on soil erosion in Spain: a review. Catena 81(1):1–11. https://doi.org/10.1016/j.catena.2010.01.001

García-Ruiz JM, López-Moreno II, Vicente-Serrano SM, Lasanta-Martínez T, Beguería S (2011) Mediterranean water resources in a global change scenario. Earth Sci Rev 105(3–4):120–139. https://doi.org/10.1016/j.earscirev.2011.01.006

García-Ruiz JM, Nadal-Romero E, Lana-Renault N, Beguería S (2013) Erosion in Mediterranean landscapes: changes and future challenges. Geomorphology 198:20–36. https://doi.org/10.1016/j.geomorph.2013.05.023

García-Ruiz JM, Beguería S, Nadal-Romero E, González-Hidalgo JC, Lana-Renault N, Sanjuán Y (2015) A meta-analysis of soil erosion rates across the world. Geomorphology 239:160–173. https://doi.org/10.1016/j.geomorph.2015.03.008

García-Tejero IF, Carbonell R, Ordoñez R, Perea Torres F, Durán Zuazo VH (2020) Conservation agriculture practices to improve the soil water management and soil carbon storage in Mediterranean rainfed agro-ecosystems. In: Meena RS (ed) Soil heal restor manag. Springer, Singapore, pp 203–230. https://doi.org/10.1007/978-981-13-8570-4_6

Gardi C, Jeffery S, Saltelli A (2013) An estimate of potential threats levels to soil biodiversity in EU. Glob Chang Biol 19(5):1538–1548. https://doi.org/10.1111/gcb.12159

Ghaley BB, Henriksen CB, Rusu T, Sandén T, Spiegel H, Menta C et al (2018) Assessment of benefits of conservation agriculture on soil functions in arable production systems in Europe. Sustain 10(3):1–17

Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. Glob Planet Chang 63(2–3):90–104. https://doi.org/10.1016/j.gloplacha.2007.09.005

Gómez JA (2017) Sustainability using cover crops in mediterranean tree crops, olives and vines – challenges and current knowledge. Hung Geogr Bull 66(1):13–28. https://doi.org/10.15201/hungeobull.66.1.2

Gómez JA, Amato M, Celano G, Koubouris GC (2008) Organic olive orchards on sloping land: more than a specialty niche production system? J Environ Manag 89:99–109. https://doi.org/10.1016/j.jenvman.2007.04.025

Gómez JA, Guzmán MG, Giráldez JV, Fereres E (2009) The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. Soil Tillage Res 106(1):137–144. https://doi.org/10.1016/j.still.2009.04.008

Gómez JA, Llewellyn C, Basch G, Sutton PB, Dyson JS, Jones CA (2011) The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. Soil Use Manag 27(4):502–514. https://doi.org/10.1111/j.1475-2743.2011.00367.x

Gómez JA, Infante-Amate J, de Molina M, Vanwalleghem T, Taguas E, Lorite I (2014) Olive cultivation, its impact on soil erosion and its progression into yield impacts in southern Spain in the past as a key to a future of increasing climate uncertainty. Agriculture 4:170–198. https://doi.org/10.3390/agriculture4020170

Gómez JA, Campos M, Guzmán G, Castillo-Llanque F, Vanwalleghem T, Lora Á, Giráldez JV (2018) Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. Environ Sci Pollut Res 25:977–989. https://doi.org/10.1007/s11356-016-8339-9

González Hidalgo JC, Peña Monné J, Luis Arrillaga M (2005) Los eventos extremos de precipitación, la variabilidad del clima y la erosión del suelo: reflexiones ante el cambio del clima en los sistemas mediterráneos. Cuat Geomorfol 19(1–2):49–62

González Hidalgo JC, Peña Monné JL, de Luis M (2007) A review of daily soil erosion in Western Mediterranean areas. Catena 71(2):193–199. https://doi.org/10.1016/j.catena.2007.03.005

González-Sánchez EJ, Ordóñez-Fernández R, Carbonell-Bojollo R, Veroz-González O, Gil-Ribes JA (2012) Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. Soil Tillage Res 122:52–60. https://doi.org/10.1016/j.still.2012.03.001

González-Sánchez EJ, Veroz-González O, Blanco-Roldán GL, Márquez-García F, Carbonell-Bojollo R (2015) A renewed view of conservation agriculture and its evolution over the last decade in Spain. Soil Tillage Res 146:204–212. https://doi.org/10.1016/j.still.2014.10.016

Goubanova K, Li L (2007) Extremes in temperature and precipitation around the Mediterranean basin in an ensemble of future climate scenario simulations. Glob Planet Chang 57(1–2):27–42. https://doi.org/10.1016/j.gloplacha.2006.11.012

Green TR (2016) Linking climate change and groundwater. In: Integr groundw manag concepts, approaches challenges. https://doi.org/10.1007/978-3-319-23576-9_5

Gucci R, Caruso G, Bertolla C, Urbani S, Taticchi A, Esposto S et al (2012) Changes of soil properties and tree performance induced by soil management in a high-density olive orchard. Eur J Agron 41:18–27. https://doi.org/10.1016/j.eja.2012.03.002

Gutiérrez GS, Durán ZVH, García TIF (2019) Response of three almond cultivars subjected to different irrigation regimes in Guadalquivir river basin. Agric Water Manag 222:72–81. https://doi.org/10.1016/j.agwat.2019.05.031

Henneron L, Bernard L, Hedde M, Pelosi C, Villenave C, Chenu C, Bertrand M, Girardin C, Blanchart E (2014) Fourteen years of evidence for positive effects of conservation agriculture and organic farming on soil life. Agron Sustain Dev 35:169–181. https://doi.org/10.1007/s13593-014-0215-8

Henry M, Valentini R, Bernoux M (2009) Soil carbon stocks in ecoregions of Africa. Biogeosci Discuss 6:797–823. https://doi.org/10.5194/bgd-6-797-2009

Hoerling M, Eischeid J, Perlwitz J, Quan X, Zhang T, Pegion P (2012) On the increased frequency of mediterranean drought. J Clim 25:2146–2161. https://doi.org/10.1175/JCLI-D-11-00296.1

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosyst Environ 103(1):1–25. https://doi.org/10.1016/j.agee.2003.12.018

Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resour Manag 21(5):775–788. https://doi.org/10.1007/s11269-006-9111-6

IPBES (2018) Summary for policymakers of the assessment report on land degradation and restoration of the intergovernmental science- policy platform on biodiversity and ecosystem services. IPBES Secretariat, Bonn, p 44

Jackson LE, Bowles TM, Ferris H, Margenot AJ, Hollander A, Garcia-Palacios P, Daufresne T, Sánchez-Moreno S (2019) Plant and soil microfaunal biodiversity across the borders between arable and forest ecosystems in a Mediterranean landscape. Appl Soil Ecol 136:122–138. https://doi.org/10.1016/j.apsoil.2018.11.015

Jat RA, Sahrawat KL, Kassam AH, Friedrich T (2014) Conservation agriculture for sustainable and resilient agriculture: global status, prospects and challenges. In: Conserv agric glob prospect challenges, pp 1–25. https://doi.org/10.1079/9781780642598.0001

Kairis O, Karavitis C, Kounalaki A, Salvati L, Kosmas C (2013) The effect of land management practices on soil erosion and land desertification in an olive grove. Soil Use Manag 29 (4):597–606. https://doi.org/10.1111/sum.12074

Kallas Z, Gómez-Limón JA, Arriaza M, Nekhay O (2006) Análisis de la demanda de bienes y servicios no comerciales procedentes de la actividad agraria: El caso del olivar de montaña andaluz. Econ Agrar y Recur Nat 6(11):49. https://doi.org/10.7201/earn.2006.11.03

Kassam A, Friedrich T, Derpsch R, Lahmar R, Mrabet R, Basch G, González-Sánchez EJ, Serraj R (2012) Conservation agriculture in the dry Mediterranean climate. Field Crop Res 132:7–17. https://doi.org/10.1016/j.fcr.2012.02.023

Kassam A, Derpsch R, Friedrich T (2014) Global achievements in soil and water conservation: the case of conservation agriculture. Int Soil Water Conserv Res 2(1):5–13. https://doi.org/10.1016/S2095-6339(15)30009-5

Kassam A, Friedrich T, Derpsch R, Kienzle J (2015) Overview of the global spread of conservation agriculture. Field Actions Sci Rep 8:53–68. https://doi.org/10.1201/9781315365800

Kassam A, Friedrich T, Derpsch R (2019) Global spread of conservation agriculture. Int J Environ Stud 76(1):29–51. https://doi.org/10.1080/00207233.2018.1494927

Keesstra SD, Bouma J, Wallinga J, Tittonell P, Smith P, Cerdà A et al (2016a) The significance of soils and soil science towards realization of the United Nations sustainable development goals. Soil 2(2):111–128. https://doi.org/10.5194/soil-2-111-2016

Keesstra S, Pereira P, Novara A, Brevik EC, Azorin-Molina C, Parras-Alcántara L, Jordán A, Cerdà A (2016b) Effects of soil management techniques on soil water erosion in apricot orchards. Sci Total Environ 551–552:357–366. https://doi.org/10.1016/j.scitotenv.2016.01.182

Kosmas C, Danalatos N, Cammeraat LH, Chabart M, Diamantopoulos J, Farand R et al (1997) The effect of land use on runoff and soil erosion rates under Mediterranean conditions. Catena 29 (1):45–59. https://doi.org/10.1016/S0341-8162(96)00062-8

Kumar S, Meena RS, Jakhar SR, Jangir CK, Gupta A, Meena BL (2019) Adaptation strategies for enhancing agricultural and environmental sustainability under current climate. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, New York, pp 226–274

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, New York, pp 337–375. https://doi.org/10.1007/978-981-13-7264-3_10

Laban P, Metternicht G, Davies J (2018) Soil biodiversity and soil organic carbon: keeping drylands alive. In: Soil biodivers soil org carbon keep. Drylands alive. IUCN, Gland. https://doi.org/10.2305/iucn.ch.2018.03.en

Lagacherie P, Coulouma G, Ariagno P, Virat P, Boizard H, Richard G (2006) Spatial variability of soil compaction over a vineyard region in relation with soils and cultivation operations. Geoderma 134(1-2):207–216. https://doi.org/10.1016/j.geoderma.2005.10.006

Lagacherie P, Álvaro-Fuentes J, Annabi M, Bernoux M, Bouarfa S, Douaoui A et al (2018) Managing Mediterranean soil resources under global change: expected trends and mitigation strategies. Reg Environ Chang 18(3):663–675. https://doi.org/10.1007/s10113-017-1239-9

Lal R (2004a) Soil carbon sequestration impacts on global climate change and food security. Science 304(5677):1623–1627. https://doi.org/10.1126/science.1097396

Lal R (2004b) Soil carbon sequestration to mitigate climate change. Geoderma 123(1–2):1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lal R (2008) Soils and sustainable agriculture. A review. Agron Sustain Dev 28(1):57–64. https://doi.org/10.1051/agro:2007025

Lal R (2014) Soil conservation and ecosystem services. Int Soil Water Conserv Res 2(3):36–47. https://doi.org/10.1016/S2095-6339(15)30021-6

Lal R (2015) Restoring soil quality to mitigate soil degradation. Sustain 7:55875–55895. https://doi.org/10.3390/su7055875

Lal R, Stewart B (2013) Principles of sustainable soil management in agroecosystems. CRC Press, Boca Raton, p 568. https://doi.org/10.1201/b14972

Lal R, Delgado JA, Groffman PM, Millar N, Dell C, Rotz A (2011) Management to mitigate and adapt to climate change. J Soil Water Conserv 66(4):276–285. https://doi.org/10.2489/jswc.66.4.276

Le Bissonnais Y, Montier C, Jamagne M, Daroussin J, King D (2002) Mapping erosion risk for cultivated soil in France. Catena 46(2–3):207–220. https://doi.org/10.1016/S0341-8162(01)00167-9

Le QB, Nkonya E, Mirzabaev A (2016) Biomass productivity-based mapping of global land degradation hotspots. In: Econ L. degrad improv - a glob assess sustain dev. Springer, New York, pp 55–84. https://doi.org/10.1007/978-3-319-19168-3_4

Lee H, Lautenbach S, Nieto APG, Bondeau A, Cramer W, Geijzendorffer IR (2019) The impact of conservation farming practices on Mediterranean agro-ecosystem services provisioning—a meta-analysis. Reg Environ Chang. https://doi.org/10.1007/s10113-018-1447-y

Linares R, de la Fuente M, Junquera P, Lissarrague JR, Baeza P (2014) Effects of soil management in vineyard on soil physical and chemical characteristics. BIO Web Conf 3:01008. https://doi.org/10.1051/bioconf/20140301008

López-Piñeiro A, Muñoz A, Zamora E, Ramírez M (2013) Influence of the management regime and phenological state of the vines on the physicochemical properties and the seasonal fluctuations of the microorganisms in a vineyard soil under semi-arid conditions. Soil Tillage Res 126:119–126. https://doi.org/10.1016/j.still.2012.09.007

Loumou A, Giourga C (2003) Olive groves: the life and identity of the Mediterranean. Agric Hum Values 20:87–95. https://doi.org/10.1023/A:1022444005336

Macci C, Doni S, Peruzzi E, Masciandaro G, Mennone C, Ceccanti B (2012) Almond tree and organic fertilization for soil quality improvement in southern Italy. J Environ Manag 95:S215–S222. https://doi.org/10.1016/j.jenvman.2010.10.050

Maetens W, Vanmaercke M, Poesen J, Jankauskas B, Jankauskiene G, Ionita I (2012a) Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: a meta-analysis of plot data. Prog Phys Geogr 90:53–62. https://doi.org/10.1177/0309133312451303

Maetens W, Poesen J, Vanmaercke M (2012b) How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean? Earth Sci Rev 115 (1–2):21–36. https://doi.org/10.1016/j.earscirev.2012.08.003

Malek Ž, Verburg PH, Geijzendorffer I, Bondeau A, Cramer W (2018) Global change effects on land management in the Mediterranean region. Glob Environ Chang 50:238–254. https://doi.org/10.1016/j.gloenvcha.2018.04.007

Manlay RJ, Feller C, Swift MJ (2007) Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. Agric Ecosyst Environ 119(3–4):217–233. https://doi.org/10.1016/j.agee.2006.07.011

MAPA (2018) Ministerio de agricultura, pesca y alimentación MAPA (2018) ESYRCE, Análisis de las técnicas de mantenimiento del suelo y de los métodos de siembra en España 2018. Available https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/cubiertas2018_tcm30-504664.pdf

MAPA (2019) Ministerio de Agricultura, Pesca y Alimentación, Anuario de estadística 2018. Madrid. p 846. NIPO: 003-19-200-0

Maracchi G, Sirotenko O, Bindi M (2005) Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe increasing clim var chang reducing vulnerability. Agric For 70:117–135. https://doi.org/10.1007/1-4020-4166-7_6

Marcolan AL, Anghinoni I (2006) Physical attributes of an ultisoland crop yield as affected by soil mobilization in no-tillage system. Rev Bras Ciênc Solo 30:163–170. https://doi.org/10.1590/S0100-06832006000100016

Marques MJ, Bienes R, Pérez-Rodríguez R, Jiménez L (2008) Soil degradation in Central Spain due to sheet water erosion by low-intensity rainfall events. Earth Surf Process Landf 33(3):414–423. https://doi.org/10.1002/esp.1564

Marques MJ, García-Muñoz S, Muñoz-Organero G, Bienes R (2010) Soil conservation beneath grass cover in hillside vineyards under mediterranean climatic conditions (Madrid, Spain). L Degrad Dev 21(2):122–131. https://doi.org/10.1002/ldr.915

Marques MJ, Bienes R, Cuadrado J, Ruiz-Colmenero M, Barbero-Sierra C, Velasco A (2015) Analysing perceptions attitudes and responses of winegrowers about sustainable land management in Central Spain. L Degrad Dev 26(5):458–467. https://doi.org/10.1002/ldr.2355

Martínez Ibarra E (2012) A geographical approach to post-flood analysis: the extreme flood event of 12 October 2007 in Calpe (Spain). Appl Geogr 32(2):490–500. https://doi.org/10.1016/j.apgeog.2011.06.003

Martínez Raya A, Durán Zuazo VH, Francia Martínez JR (2006) Soil erosion and runoff response to plant-cover strips on semiarid slopes (SE Spain). L Degrad Dev 17(1):1–11. https://doi.org/10.1002/ldr.674

Martínez-Casasnovas JA, Ramos MC (2006) The cost of soil erosion in vineyard fields in the Penedès-Anoia Region (NE Spain). Catena 68(2–3):194–199. https://doi.org/10.1016/j.catena.2006.04.007

Martínez-Casasnovas JA, Ramos MC, Ribes-Dasi M (2002) Soil erosion caused by extreme rainfall events: Mapping and quantification in agricultural plots from very detailed digital elevation models. Geoderma 105(1–2):125–140. https://doi.org/10.1016/S0016-7061(01)00096-9

Martínez-Mena M, Lopez J, Almagro M, Boix-Fayos C, Albaladejo J (2008) Effect of water erosion and cultivation on the soil carbon stock in a semiarid area of South-East Spain. Soil Tillage Res 99(1):119–129. https://doi.org/10.1016/j.still.2008.01.009

Martínez-Mena M, López J, Almagro M, Albaladejo J, Castillo V, Ortiz R, Boix-Fayos C (2012) Organic carbon enrichment in sediments: effects of rainfall characteristics under different land uses in a Mediterranean area. Catena 94:36–42. https://doi.org/10.1016/j.catena.2011.02.005

Martínez-Mena M, Garcia-Franco N, Almagro M, Ruiz-Navarro A, Albaladejo J, de Aguilar JM, Gonzalez D, Querejeta JI (2013) Decreased foliar nitrogen and crop yield in organic rainfed almond trees during transition from reduced tillage to no-tillage in a dryland farming system. Eur J Agron 49:149–157. https://doi.org/10.1016/j.eja.2013.04.006

Meena RS, Kumar S, Yadav GS (2019) Soil carbon sequestration in crop production. In: Meena RS (ed) Nutrient dynamics for sustainable crop production. Springer, New York, pp 1–39. https://doi.org/10.1007/978-981-13-8660-2_1

Meena RS, Lal R, Yadav GS (2020) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Montanarella L (2007) Trends in land degradation in Europe. In: Environ sci eng (subseries environ sci). Springer, Berlin, pp 83–104. https://doi.org/10.1007/978-3-540-72438-4_5

Montanaro G, Dichio B, Briccoli Bati C, Xiloyannis C (2012) Soil management affects carbon dynamics and yield in a Mediterranean peach orchard. Agric Ecosyst Environ 161:46–54. https://doi.org/10.1016/j.agee.2012.07.020

Montanaro G, Xiloyannis C, Nuzzo V, Dichio B (2017) Orchard management, soil organic carbon and ecosystem services in Mediterranean fruit tree crops. Sci Hortic 217:92–101. https://doi.org/10.1016/j.scienta.2017.01.012

Montgomery DR (2007) Soil erosion and agricultural sustainability. Proc Natl Acad Sci U S A 104:13268–13272. https://doi.org/10.1073/pnas.0611508104

Mueller L, Schindler U, Mirschel W, Shepherd TG, Ball BC, Helming K, Rogasik J, Eulenstein F, Wiggering H (2010) Assessing the productivity function of soils. A review. Agron Sustain Dev 30:601–614. https://doi.org/10.1051/agro/2009057

Muñoz-Rojas M, Jordán A, Zavala LM, González-Peñaloza FA, De La Rosa D, Pino-Mejias R, Anaya-Romero M (2013) Modelling soil organic carbon stocks in global change scenarios: a CarboSOIL application. Biogeosciences 10(12):8253–8268. https://doi.org/10.5194/bg-10-8253-2013

Muñoz-Rojas M, Abd-Elmabod SK, Zavala LM, De la Rosa D, Jordán A (2017) Climate change impacts on soil organic carbon stocks of Mediterranean agricultural areas: a case study in Northern Egypt. Agric Ecosyst Environ 238:142–152. https://doi.org/10.1016/j.agee.2016.09.001

Nicholls CI, Altieri MA, Ponti L (2008) Enhancing plant diversity for improved insect pest management in Northern California organic vineyards. Acta Hortic 785:263–278. https://doi.org/10.17660/ActaHortic.2008.785.32

Nie X, Li Z, He J, Huang J, Zhang Y, Huang B, Ma W, Lu Y, Zeng G (2015) Enrichment of organic carbon in sediment under field simulated rainfall experiments. Environ Earth Sci 74 (6):5417–5425. https://doi.org/10.1007/s12665-015-4555-8

Nieto OM, Castro J, Fernández-Ondoño E (2013) Conventional tillage versus cover crops in relation to carbon fixation in Mediterranean olive cultivation. Plant Soil 365(1–2):321–335. https://doi.org/10.1007/s11104-012-1395-0

Novara A, Gristina L, Saladino SS, Santoro A, Cerdà A (2011) Soil erosion assessment on tillage and alternative soil managements in a Sicilian vineyard. Soil Tillage Res 117:140–147. https://doi.org/10.1016/j.still.2011.09.007

OIV (2019) International Organisation of Vine and Wine Intergovernmental Organisation. Statistical report on world vitiviniculture. http://www.oiv.int/public/medias/6782/oiv-2019-statistical-report-on-world-vitiviniculture.pdf

Olesen JE, Bindi M (2002) Consequences of climate change for European agricultural productivity, land use and policy. Eur J Agron 16(4):239–262. https://doi.org/10.1016/S1161-0301(02)00004-7

Orgiazzi A, Panagos P (2018) Soil biodiversity and soil erosion: It is time to get married. Glob Ecol Biogeogr 27(10):1155–1167. https://doi.org/10.1111/geb.12782

Palese AM, Vignozzi N, Celano G, Agnelli AE, Pagliai M, Xiloyannis C (2014) Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. Soil Tillage Res 144:96–109. https://doi.org/10.1016/j.still.2014.07.010

Palese AM, Ringersma J, Baartman JEM, Peters P, Xiloyannis C (2015) Runoff and sediment yield of tilled and spontaneous grass-covered olive groves grown on sloping land. Soil Res 53 (5):542–552. https://doi.org/10.1071/SR14350

Panagos P, Borrelli P, Poesen J, Ballabio C, Lugato E, Meusburger K, Montanarella L, Alewell C (2015a) The new assessment of soil loss by water erosion in Europe. Environ Sci Pol 54:438–447. https://doi.org/10.1016/j.envsci.2015.08.012

Panagos P, Ballabio C, Borrelli P, Meusburger K, Klik A, Rousseva S et al (2015b) Rainfall erosivity in Europe. Sci Total Environ 511:801–814. https://doi.org/10.1016/j.scitotenv.2015.01.008

Panagos P, Standardi G, Borrelli P, Lugato E, Montanarella L, Bosello F (2018) Cost of agricultural productivity loss due to soil erosion in the European Union: from direct cost evaluation approaches to the use of macroeconomic models. L Degrad Dev 29(3):471–484. https://doi.org/10.1002/ldr.2879

Pappalardo SE, Gislimberti L, Ferrarese F, De Marchi M, Mozzi P (2019) Estimation of potential soil erosion in the Prosecco DOCG area (NE Italy), toward a soil footprint of bottled sparkling wine production in different land-management scenarios. PLoS One 14(5):1–13. https://doi.org/10.1371/journal.pone.0210922

Paustian K, Six J, Elliott ET, Hunt HW (2000) Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48:147–163. https://doi.org/10.1023/A:1006271331703

Peñarrocha D, Estrela MJ, Millán M (2002) Classification of daily rainfall patterns in a Mediterranean area with extreme intensity levels: the Valencia region. Int J Climatol 22(6):677–695. https://doi.org/10.1002/joc.747

Pérès G, Bellido A, Curmi P, Marmonier P, Cluzeau D (2010) Relationships between earthworm communities and burrow numbers under different land use systems. Pedobiologia 54(1):37–44. https://doi.org/10.1016/j.pedobi.2010.08.006

Pimentel D (2006) Soil erosion: a food and environmental threat. Environ Dev Sustain 8:119–137. https://doi.org/10.1007/s10668-005-1262-8

Pimentel D, Burgess M (2013) Soil erosion threatens food production. Agriculture 3(3):443–463. https://doi.org/10.3390/agriculture3030443

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M et al (1995) Environmental and economic costs of soil erosion. Science 267(5201):1117–1123. https://doi.org/10.1126/science.267.5201.1117

Pires LF, Borges JAR, Rosa JA, Cooper M, Heck RJ, Passoni S, Roque WL (2017) Soil structure changes induced by tillage systems. Soil Tillage Res 165:66–79. https://doi.org/10.1016/j.still.2016.07.010

Pisante M, Stagnari F, Grant CA (2012) Agricultural innovations for sustainable crop production intensification. Ital J Agron 7(40):300–311. https://doi.org/10.4081/ija.2012.e40

Prosdocimi M, Jordán A, Tarolli P, Keesstra S, Novara A, Cerdà A (2016) The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci Total Environ 547:323–330. https://doi.org/10.1016/j.scitotenv.2015.12.076

Quinton JN, Govers G, Van Oost K, Bardgett RD (2010) The impact of agricultural soil erosion on biogeochemical cycling. Nat Geosci 3:311–314. https://doi.org/10.1038/ngeo838

Rajan K, Natarajan A, Anil Kumar KS, Badrinath MS, Gowda RC (2010) Soil organic carbon - the most reliable indicator for monitoring land degradation by soil erosion. Curr Sci 99(6):823–827

Ramos MC (2016) Soil losses in rainfed Mediterranean vineyards under climate change scenarios. The effects of drainage terraces. AIMS Agric Food 1(2):124–143. https://doi.org/10.3934/agrfood.2016.2.124

Ramos MC, Durán B (2014) Assessment of rainfall erosivity and its spatial and temporal variabilities: case study of the Penedès area (NE Spain). Catena 123:135–147. https://doi.org/10.1016/j.catena.2014.07.015

Ramos MC, Martínez-Casasnovas JA (2006) Nutrient losses by runoff in vineyards of the Mediterranean Alt Penedès region (NE Spain). Agric Ecosyst Environ 113(1–4):356–363. https://doi.org/10.1016/j.agee.2005.10.009

Ramos MC, Martínez-Casasnovas JA (2007) Soil loss and soil water content affected by land levelling in Penedès vineyards, NE Spain. Catena 71(2):210–217. https://doi.org/10.1016/j.catena.2007.03.001

Ramos MC, Martínez-Casasnovas JA (2009) Impacts of annual precipitation extremes on soil and nutrient losses in vineyards of NE Spain. Hydrol Process 23(2):224–235. https://doi.org/10.1002/hyp.7130

Ramos MC, Martínez-Casasnovas JA (2015) Soil water content, runoff and soil loss prediction in a small ungauged agricultural basin in the Mediterranean region using the soil and water assessment tool. J Agric Sci 153(3):481–496. https://doi.org/10.1017/S0021859614000422

Ramos ME, Benítez E, García PA, Robles AB (2010) Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: effects on soil quality. Appl Soil Ecol 44(1):6–14. https://doi.org/10.1016/j.apsoil.2009.08.005

Rickson RJ (2014) Can control of soil erosion mitigate water pollution by sediments? Sci Total Environ 468–469:1187–1197. https://doi.org/10.1016/j.scitotenv.2013.05.057

Robledano-Aymerich F, Romero-Díaz A, Belmonte-Serrato F, Zapata-Pérez VM, Martínez-Hernández C, Martínez-López V (2014) Ecogeomorphological consequences of land abandonment in semiarid Mediterranean areas: Integrated assessment of physical evolution and biodiversity. Agric Ecosyst Environ 197:222–242. https://doi.org/10.1016/j.agee.2014.08.006

Rockström J, Karlberg L, Wani SP, Barron J, Hatibu N, Oweis T, Bruggeman A, Farahani J, Qiang Z (2010) Managing water in rainfed agriculture-the need for a paradigm shift. Agric Water Manag 97(4):543–550. https://doi.org/10.1016/j.agwat.2009.09.009

Rodrigo Comino J, Ruiz Sinoga JD, Senciales González JM, Guerra-Merchán A, Seeger M, Ries JB (2016) High variability of soil erosion and hydrological processes in Mediterranean hillslope vineyards (Montes de Málaga, Spain). Catena 145:274–284. https://doi.org/10.1016/j.catena.2016.06.012

Rodrigo-Comino J, Martínez-Hernández C, Iserloh T, Cerdà A (2018a) Contrasted impact of land abandonment on soil erosion in Mediterranean agriculture fields. Pedosphere 28(4):617–631. https://doi.org/10.1016/S1002-0160(17)60441-7

Rodrigo-Comino J, Brevik EC, Cerdà A (2018b) The age of vines as a controlling factor of soil erosion processes in Mediterranean vineyards. Sci Total Environ 616–617:1163–1173. https://doi.org/10.1016/j.scitotenv.2017.10.204

Rodríguez-Lizana A, Espejo-Pérez AJ, González-Fernández P, Ordóñez-Fernández R (2008) Pruning residues as an alternative to traditional tillage to reduce erosion and pollutant dispersion in olive groves. Water Air Soil Pollut 193:165–173. https://doi.org/10.1007/s11270-008-9680-5

Romero Díaz A, Martínez Hernández C, Belmonte Serrato F (2012) Cambios de usos del suelo en la región de Murcia. El almendro como cultivo de referencia y su relación con los procesos de erosión. Nimbus 29–30:607–626

Ruiz-Colmenero M, Bienes R, Marques MJ (2011) Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. Soil Tillage Res 117:211–223. https://doi.org/10.1016/j.still.2011.10.004

Ruiz-Colmenero M, Bienes R, Eldridge DJ, Marques MJ (2013) Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. Catena 104:153–160. https://doi.org/10.1016/j.catena.2012.11.007

Salvati L (2010) Exploring the relationship between agricultural productivity and land degradation in a dry region of southern Europe. New Medit 9(1):35–40

Sánchez-Moreno S, Castro J, Alonso-Prados E, Alonso-Prados JL, García-Baudín JM, Talavera M, Durán-Zuazo VH (2015) Tillage and herbicide decrease soil biodiversity in olive orchards. Agron Sustain Dev 35(2):691–700. https://doi.org/10.1007/s13593-014-0266-x

Sastre B, Barbero-Sierra C, Bienes R, Marques MJ, García-Díaz A (2017) Soil loss in an olive grove in Central Spain under cover crops and tillage treatments, and farmer perceptions. J Soils Sediments 17(3):873–888. https://doi.org/10.1007/s11368-016-1589-9

Schulte RPO, Bampa F, Bardy M, Coyle C, Creamer RE, Fealy R, Gardi C, Ghaley BB, Jordan P, Laudon H, O'Donoghue C, Ó'hUallacháin D, O'Sullivan L, Rutgers M, Six J, Toth GL, Vrebos

D (2015) Making the most of our land: managing soil functions from local to continental scale. Front Environ Sci 3:81. https://doi.org/10.3389/fenvs.2015.00081

Simoes MP, Belo AF, Pinto-Cruz C, Pinheiro AC (2014) Natural vegetation management to conserve biodiversity and soil water in olive orchards. Span J Agric Res 12(3):633–643. https://doi.org/10.5424/sjar/2014123-5255

Six J, Ogle SM, Breidt FJ, Conant RT, Mosiers AR, Paustian K (2004) The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob Chang Biol 10(2):155–160. https://doi.org/10.1111/j.1529-8817.2003.00730.x

Smerdon BD (2017) A synopsis of climate change effects on groundwater recharge. J Hydrol 555:125–128. https://doi.org/10.1016/j.jhydrol.2017.09.047

Sofo A, Manfreda S, Fiorentino M, Dichio B, Xiloyannis C (2008) The olive tree: a paradigm for drought tolerance in Mediterranean climates. Hydrol Earth Syst Sci 12(1):293–301. https://doi.org/10.5194/hess-12-293-2008

Sofo A, Ciarfaglia A, Scopa A, Camele I, Curci M, Crecchio C, Xiloyannis C, Palese AM (2014) Soil microbial diversity and activity in a Mediterranean olive orchard using sustainable agricultural practices. Soil Use Manag 30(1):160–167. https://doi.org/10.1111/sum.12097

Soriano MA, Álvarez S, Landa BB, Gómez JA (2014) Soil properties in organic olive orchards following different weed management in a rolling landscape of Andalusia, Spain. Renew Agric Food Syst 29(1):83–91. https://doi.org/10.1017/S1742170512000361

Spurgeon DJ, Keith AM, Schmidt O, Lammertsma DR, Faber JH (2013) Land-use and land-management change: relationships with earthworm and fungi communities and soil structural properties. BMC Ecol 13(46). https://doi.org/10.1186/1472-6785-13-46

Tommaso C, Emanuele B, Guido P, Lucia P, Vincenza CM, Riccardo V (2018) Soil organic carbon pool's contribution to climate change mitigation on marginal land of a Mediterranean montane area in Italy. J Environ Manag 218:593–601. https://doi.org/10.1016/J.JENVMAN.2018.04.093

Turral H, Burke J, Faures JM, Faures JM (2011) Climate change, water and food security. Rome Food Agric. Organ. United Nations

Turrini A, Caruso G, Avio L, Gennai C, Palla M, Agnolucci M, Tomei PE, Giovannetti M, Gucci R (2017) Protective green cover enhances soil respiration and native mycorrhizal potential compared with soil tillage in a high-density olive orchard in a long term study. Appl Soil Ecol 116:70–78. https://doi.org/10.1016/j.apsoil.2017.04.001

USDA (2017) Tree nuts annual EU-28. Glob. Agric. Inf. Netw. https://gain.fas.usda.gov/Recent/GAIN Publications/Tree Nuts Annual_Madrid_EU-28_9-18-2017.pdf

Valdes-Abellan J, Pardo MA, Tenza-Abril AJ (2017) Observed precipitation trend changes in the western Mediterranean region. Int J Climatol 37(51):1285–1296. https://doi.org/10.1002/joc.4984

Van Dijck SJE, Van Asch TWJ (2002) Compaction of loamy soils due to tractor traffic in vineyards and orchards and its effect on infiltration in southern France. Soil Tillage Res 63(3–4):141–153. https://doi.org/10.1016/S0167-1987(01)00237-9

van Es HM, Magdoff F (2009) Building soils for better crops (Third edit.). Sustainable agriculture research and education (SARE) program

Vanmaercke M, Poesen J, Maetens W, de Vente J, Verstraeten G (2011) Sediment yield as a desertification risk indicator. Sci Total Environ 409(9):1715–1725. https://doi.org/10.1016/j.scitotenv.2011.01.034

Vastola A, Zdruli P, D'Amico M, Pappalardo G, Viccaro M, Di Napoli F, Cozzi M, Romano S (2017) A comparative multidimensional evaluation of conservation agriculture systems: a case study from a Mediterranean area of Southern Italy. Land Use Policy 68:326–333. https://doi.org/10.1016/j.landusepol.2017.07.034

Verheijen FGA, Jones RJA, Rickson RJ, Smith CJ (2009) Tolerable versus actual soil erosion rates in Europe. Earth Sci Rev 94(1–4):23–38. https://doi.org/10.1016/j.earscirev.2009.02.003

Verstraeten G, Poesen J, Demarée G, Salles C (2006) Long-term (105 years) variability in rain erosivity as derived from 10-min rainfall depth data for Ukkel (Brussels, Belgium): Implications for assessing soil erosion rates. J Geophys Res Atmos 111(22). https://doi.org/10.1029/2006JD007169

Vicente-Serrano SM, Rodríguez-Camino E, Domínguez-Castro F, El Kenawy A, Azorín-Molina C (2017) An updated review on recent trends in observational surface atmospheric variables and their extremes over Spain. Cuad Investig Geogr 43(1):209–232. https://doi.org/10.18172/cig.3134

Vicente-Vicente JL, Gómez-Muñoz B, Hinojosa-Centeno MB, Smith P, Garcia-Ruiz R (2017) Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management. Agric Ecosyst Environ 245:135–146. https://doi.org/10.1016/j.agee.2017.05.020

Wagg C, Bender SF, Widmer F, Van Der Heijden MGA (2014) Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proc Natl Acad Sci U S A 111(14):5266–5270. https://doi.org/10.1073/pnas.1320054111

Wall DH, Nielsen UN, Six J (2015) Soil biodiversity and human health. Nature 528:69–76. https://doi.org/10.1038/nature15744

Wardle DA, Bardgett Richard D, Klironomos John N, Heikki S, van der Putten WH, Wall Diana H (2004) Ecological linkages between aboveground and belowground biota. Science 304 (5677):1629–1633

Winter S, Bauer T, Strauss P, Kratschmer S, Paredes D, Popescu D et al (2018) Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis. J Appl Ecol 55(5):2484–2495. https://doi.org/10.1111/1365-2664.13124

WWAP(2012) World Water development report volume 4: managing water under uncertainty and risk. Water demand What drives Consum. https://doi.org/10.1608/FRJ-3.1.2

Zalidis G, Stamatiadis S, Takavakoglou V, Eskridge K, Misopolinos N (2002) Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology. Agric Ecosyst Environ 88(2):137–146. https://doi.org/10.1016/S0167-8809(01)00249-3

Zaller JG, Cantelmo C, Dos Santos G, Muther S, Gruber E, Pallua P et al (2018) Herbicides in vineyards reduce grapevine root mycorrhization and alter soil microorganisms and the nutrient composition in grapevine roots, leaves, xylem sap and grape juice. Environ Sci Pollut Res 25 (23):23215–23226. https://doi.org/10.1007/s11356-018-2422-3

Zhang G (2016) Characteristics of runoff nutrient loss and particle size distribution of eroded sediment under varied rainfall intensities. In: 4th Int. Conf. Mach. Mater. Comput Technol (ICMMCT 2016). https://doi.org/10.2991/icmmct-16.2016.119

Efficient Use of Soil in Silvopastoral Systems of Native Forests

14

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Abstract

In agriculture and forestry, the soil is one of the essential natural resources. Efficient soil use is essential to achieve sustainable development and face current global problems, such as food security and climate change. A better understanding of the dynamics of this resource and parallel actions of soil conservation and restoration should be incorporated into agricultural and forestry practices. The American Gran Chaco is a transition area between the tropics and the temperate zone, corresponding to savannas and semi-arid forests. For decades, the combination of high input agriculture, exceptionally profitable in the short term, with livestock in implanted pastures, accelerated the massive clearing of shrubs and native forests, which has caused negative impacts on biodiversity, on the quality of soils and therefore on the sustainability of production processes. Silvopastoral systems (SSP) are agroforestry systems with a promising approach to achieve sustainability of agroecosystems and improve forest conservation. These production systems combine grasses, trees, and animals that interact on the same surface unit while obtaining different products such as meat and wood. Silvopastoral systems are designed to increase efficiency in the use of resources, improve and diversify production, and conserve a large part of ecosystem services. Currently, in the Argentine Chaco, SSPs are designed from secondary forests that were degraded in earlier times. The objective of this chapter was to review knowledge about the impact of forest management with livestock on the soil of this region. For the habilitation of these forests in silvopastoral systems and efficient soil use, the authors recommend the low-intensity roller-chopping (RBI) method, a selective mechanical alteration of the vegetation, with the sowing of pastures, which tries to maintain biodiversity, natural regeneration of woodland and soil conditions, and improve system productivity. Over several decades, the authors have studied the interaction of RBI on soil quality, by evaluating soil indicators. The effect of RBI has been shown to depend on the ecological site, vegetation cover, and grazing. Silvopastoral systems maintain soil properties, such as moisture, bulk density, total organic carbon, particulate organic carbon, and carbon from microbial biomass, of utmost importance in semi-arid environments. Furthermore, SSPs have been found to have minimal impact on the diversity of soil microbial communities. Therefore, it can be affirmed in the medium term that SSPs are favorable for this region.

Keywords

Chaco region · Disturbance · Efficiency · Forest management · Grazing · Low-intensity roller-chopping · Silvopastoral · Soil carbon · Soil indicators · Soil microbial biomass · Tree cover

Abbreviations

C	Carbon
C_0	Mineralizable potential carbon
CO_2	Carbon dioxide
Dh-asa	Dehydrogenase activity
FMIL	Forest management incorporating livestock
GFE	Easily removable glomalin
GT	Total glomalin
Ha	Hectare
INTA	National Institute of Agricultural Technology of Argentina
Kc	Mineralization rate
Kg	Kilogram
LL	Lowland
M	Meter
M	*Ziziphus mistol* (Mistol)
MAGYP	Ministry of Agriculture, Livestock and Fisheries
MBC	Microbial biomass carbon
MD	Midland
N	Nitrogen
POC	Particulate organic carbon
Qb	*Aspidosperma quebracho blanco* (Quebracho blanco)
Qc	*Schinopsis lorentzii* (Quebracho colorado)
qCO_2	Microbial metabolic quotient
RBI	Low-intensity roller-chopping
RE	Soil respiration
SBD	Soil bulk density
SGAYDS	General Secretariat of Environment and Sustainable Development
SOM	Soil organic matter
SSP	Silvopastoral system
t	Tons
TN	Total nitrogen
TOC	Total organic carbon
UG	Livestock unit
UP	Upland
mm	Millimeter
cm	Centimeter
g	Grams

14.1 Introduction

Soil is one of the main natural resources in agricultural and forestry activity. The efficient use of this resource is essential to achieve sustainable development and to face current problems as important as the food crisis or climate change globally. In recent decades, intensive agricultural practices have been developed and applied to achieve high agricultural production, with very negative environmental consequences. In the same way, large disturbances of natural or anthropogenic origin have progressively decreased the world's forest area, degrading large areas of soil. Efficient land use should be accompanied by a greater understanding of the dynamics of this resource, and parallel actions for soil conservation and restoration, so that they are incorporated into agricultural and forestry practices.

The Gran Chaco is an extensive plain of around 1,200,000 km^2 (kilometers). It includes part of four countries: north-central Argentina (59%), western Paraguay (23%), southeast Bolivia (13%), and the west end of Brazil (5%) (Hueck 1972). It extends from tropical latitudes (18°S) to subtropical environments (31°S). It presents a great variety of climates and reliefs that give rise to a wide diversity of environments: from pastures, estuaries, and dry and flooded savannas, to bathed, saline areas, saws, and rivers; and, of course, a large area and diversity of forests and shrubs (Caballero et al. 2014). It comprises two large ecoregions, the Wet Chaco and Dry Chaco, represented by different ecosystems in each country (Morello 2012; Mereles and Yanosky 2013). The topography is predominantly flat, with some low-rise elevations towards the western limit in Argentina and Bolivia, and also in a sector of the Paraguayan–Bolivian border. The soils derive from the stockpiling of river and wind sediments (loess) during the tertiary and quaternary. The Gran Chaco has a climate with high seasonality, with maximum summer temperatures of up to 49 °C and potent winter frosts. The rain of this region ranged between less than 500-millimeter (mm) $year^{-1}$ in the west to 1000 mm $year^{-1}$ in the east, being the dry season in the winter and the spring, and the rainy season occurs in the summer (Morello 2012).

The Gran Chaco is the largest seasonally dry subtropical forest in the world (Carranza et al. 2015). The vegetation of the Chaco region is a mosaic of xerophytic forests, woodlands, scrubs, savannas, and grasslands (Bucher and Saravia Toledo 2001; Kunst et al. 2014). Soil and drainage define different types of vegetation, about the geomorphological processes associated with water runoff. In the ecological upland (UP) sites, there are hardwood forests, and in the intermediate and lowlands (LL) sites, the forests and savannas (maintained by fire) are present (Kunst et al. 2014).

The Gran Chaco is a transition area between the tropics and the temperate zone, corresponding to savannas and semi-arid forests (Morello and Adámoli 1974). These ecosystems have high biodiversity (Carranza et al. 2015) and provide numerous ecosystem services (Conti and Díaz 2013), including carbon (C) sequestration. Manrique et al. (2009) estimated that the Chaco forest sequesters 105.45 tons carbon dioxide per hectare (t CO_2 ha^{-1}), mainly in woody vegetation and soil (88% of the total).

For decades, the combination of high input agriculture, exceptionally profitable in the short term, with livestock in implanted pastures accelerated the massive clearing of shrubs and native forests at rates that exceed global trends (2.2% $year^{-1}$) (Zak et al. 2004; Vallejos et al. 2015; Caldas et al. 2015). The consequences were the loss and fragmentation of environments and habitats, which has caused negative impacts on biodiversity, on the quality of soils, and therefore on the sustainability of production processes (Vallejos et al. 2015). It highlights the conflict between the search for high agricultural yields and the low environmental impact. Stavi et al. (2016) indicate the importance of establishing sustainable agricultural systems that allow a certain degree of intensity. That is why, currently, integrated and moderate-intensity agricultural systems are being promoted. The objective of these systems is to maintain high yields while maintaining natural environments and resources.

In Argentina, from the public institutions and civil organizations, the sustainable use of forests and pastures is promoted e.g. Law 26.331 of Native Forest Management, an agreement between SGAYDS (General Secretariat of Environment and Sustainable Development) and MAGYP (Ministry of Agriculture, Livestock and Fisheries)-2015; promotion of forest management with integrated livestock, Program of National Action to Combat Desertification (Resolution SGAYDS 70/2019). In this context, silvopastoral systems (SSPs) represent a sustainable alternative (Meena et al. 2017).

Silvopastoral are integral management systems, which involve woody perennial species (trees or shrubs), herbaceous forage, and livestock in the same land unit at the same time (Peri et al. 2016a, b, c; Kumar et al. 2017; Sharma et al. 2019). They are characterized by being highly diversified and self-sufficient. With proper agroforestry management, SSPs favor natural processes and biological interactions, improve edaphic quality, decrease dependence on external chemical inputs, and increase agricultural productivity; they also provide various environmental services (for example, C sequestration, erosion control, protection of biodiversity and water resources) (Vallejo-Quintero 2013; Chará et al. 2015; Varma et al. 2017; Meena et al. 2018).

In the Gran Chaco, SSPs in native forest conserve around 60% of the forest's C stock (Fernández et al. 2018) and are imperative in the conservation of soil C (Albanesi et al. 2013a, b). This is very important since, in these ecosystems, the soil has the highest reserves of C (>74%) (Conti et al. 2014). However, with increase in disturbances to control shrubbing, the C stock decreases (Fernández et al. 2018). Laino et al. (2017) suggested that the sustainable use of the forests of the Gran Chaco is a great way for their conservation. However, the sustainability of SSP in the Gran Chaco region must still be evaluated and monitored, and for this, it is essential to consider the concept of soil quality.

14.2 Soil Quality and Functions

Since the 1990s, studies on soil quality have been increasing, however, contrary to other concepts such as air and water quality; there is still no regulation to establish soil quality, nor a consensus on its concept (Bünemann et al. 2018). At present, several meanings of soil quality have emerged, mostly related to its functions in natural and agricultural ecosystems (Araújo et al. 2012). Soil quality is the ability of a specific type of soil to function, within natural or managed limits, to maintain the productivity of plants and animals, maintain or improve the quality of water and air, and support human health and housing (Karlen et al. 1997; Wienhold et al. 2004). This definition speaks of the function of the soil and includes the principles of sustainability. Soil functions are the support of ecosystem services (Glenk et al. 2012); include, among others: the cycle of nutrients, water and other products, biomass, biodiversity conservation and C stock. Soil quality cannot be measured directly, so it is necessary to evaluate a set of quality indicators (Bone et al. 2014). A variety of physical, chemical, and biological characteristics can be considered as soil quality indicators (Liu et al. 2006; Rani et al. 2019; Kumar et al. 2020); these indicators should be selected because of ecological site, use and management of soil (Cardoso et al. 2013), and scale of study (plots, landscapes, or regions) (Albanesi et al. 2013a, b; Paz-Ferreiro and Fu 2016). The interpretation of the indicators should be made comprehensively; many authors suggested the combination of some of them in models to create a unique value of general soil quality index (Bone et al. 2014; Zornoza et al. 2015; Paz-Ferreiro and Fu 2016).

The latter emerges as a separate function, given the importance of C and given the current global circumstances of climate change (Cardoso et al. 2013; Burbano-Orjuela 2016). Disturbances, natural or anthropic, affect functions of soil; therefore, it is quality. The evaluation of quality is not easy since it is dynamic and may change in the short term. These changes are a function of specific characteristics of the soil, of environmental conditions, and the management practices (Navarrete Segueda et al. 2011; Albanesi et al. 2013a, b; Cardoso et al. 2013).

The indices or indicators can be used in comparative evaluations, to determine the differences in the attributes and functions of the soil among management practices. They can also be used in dynamic assessments, over time, to assess how soil management decisions affect use-dependent soil properties (Wienhold et al. 2004). In both comparative and dynamic evaluations, it is necessary to establish, for each indicator, a reference point (baseline) and specify the critical limits (thresholds) beyond which the change becomes irreversible (Bouma 2010; Araújo et al. 2012).

There are different approaches to establish reference levels; one of them considers the soil properties capable of maintaining high productivity and causing minimal disturbance to the environment. The other approach considers the properties of a climax soil developed under the climax vegetation at the site to be evaluated (Gil-Sotres et al. 2005; Li et al. 2013). This latter approach is used in most of the system studies in the Chaco region (Caruso et al. 2012; Wingeyer et al. 2015; Rojas et al. 2016). When assessing soil quality, a minimum set of indicators capable of describing the complexity of the soil system should be included (Cardoso et al. 2013; Bünemann et al. 2018).

14.3 Soil Indicators

Physical indicators of the soil are those that are associated with the efficient use of water and nutrients. These include soil structure, bulk density, aggregate stability, water infiltration, and soil depth (García et al. 2012). Also, Rabot et al. (2018) considered porosity, macro-porosity, pore distances, and pore connectivity as the most relevant physical indicators for various soil functions. Other authors, in systems under forest, included water availability or water retention capacity under this group (Zornoza et al. 2015; Toledo et al. 2018).

In Gran Chaco ecosystems, the most commonly used physical indicators are bulk density, the stability of soil aggregates, and erodible fraction. In native forests from clay soils to loam soils, low apparent density was recorded (for example, 0.6–1.2 g cm^{-3}—grams per cubic centimeter). It has also been reported that soil aggregates have stability from regular to excellent (Caruso et al. 2012; Anriquez et al. 2016; Rojas et al. 2016). Anthropogenic interventions increase the bulk density and decrease the aggregate stability of soil (Bonino 2006; Carranza and Ledesma 2009). However, SSPs in native forests generally maintain these properties (Caruso et al. 2012; Anriquez et al. 2016), especially in those where there are significant trees cover (Anriquez et al. 2005) and where grazing is controlled (Carranza and Ledesma 2009). Therefore, grazing intensity and vegetation cover must be regulated according to the climatic conditions of the ecological site (Abdalla et al. 2018).

Chemical indicators of soil quality are those that affect the soil–plant relationship. They are associated with soil fertility, so they are crucial for the establishment and survival of the plant. It includes soil pH, electrical conductivity, soil water quality, buffering capacity, nutrient availability for plants and microorganisms, cation exchange capacity, organic matter content, organic C and nitrogen (N) (of total fraction of organic matter and particulate fraction) (Navarrete Segueda et al. 2011; Jangir et al. 2017, 2019). In the ecosystems of the Chaco region, the most commonly used chemical indicators are total organic carbon (TOC) in soil and its fractions (particulate C and associated C with soil minerals). The physically separated organic fractions have proven to be sensitive indicators to different agronomic practices (Abril and Bucher 1999, 2001; Anriquez et al. 2005; Galantini and Suñer 2008; Silberman et al. 2015; Gamarra Lezcano et al. 2018).

In arid areas, Abril (2015) highlighted the balance of soil C as an indicator to assess the sustainability of productive practices. In pasture sites, Dlamini et al. (2016) use the stock of C as a sensitive indicator to management practices. At these sites, they say that a large proportion of TOC remains in the upper layer of soil (0–30 cm), the pasture management significantly affects, and environmental conditions in which they are found. That is why in dry climates (<600 mm) TOC reserves are more vulnerable since inadequate management produces higher losses of TOC compared to wet climates (>1000 mm). On the other hand, Bonino (2006), demonstrated, in Dry Chaco, that TOC indicator is more sensitive to differences in vegetation biomass than to changes in land use. For the Chaco region, Camardelli et al. (2005) recommend the following soil indicators: TOC, total organic matter, associated organic C, and particulate organic carbon (POC) the Chaco region. Their use predicts early losses of soil quality, which can prevent fall in productivity of systems.

Another of soil indicators used is N, which constitutes the most limiting nutrient for plants productivity in arid and semi-arid areas (after water) (Celaya Michel and Castellanos Villegas 2010). Regarding this indicator, Albanesi et al. (2003) considered that initial vegetation (grassland or forest) and relief affect the distribution of this element. In pasture sites, Gonzalez et al. (2001) used the content of total nitrogen (TN) and soil nitrates as sensitive indicators to assess the effects of the prescribed fire frequency.

Physical and chemical indicators are the primary indicators being used to assess soil quality. Anyway, when we want to evaluate the quality of soil, it must include a minimum set of biological and biochemical indicators capable of describing the complexity of the soil system. The soil microbiome is responsible for different functions in the soil system, such as the generation of humic substances, the decomposition of the soil organic matter (SOM), mineralization and the nutrient cycle, degradation of celluloses and contaminating substances (Gonzalez et al. 2001; Paz-Ferreiro and Fu 2016). Among biological indicators, those parameters are considered that allow determining the structure of microbial community present in soil (size, composition, etc.) and those that determine its function (biological activity in general or involved in specific processes) (Muñoz-Rojas et al. 2016). Direct relationships between structure and function of microbial communities are challenging to elucidate; both these parameters characterize the response of microorganisms to management activities and therefore to change in land use (Bissett et al. 2013; Albanesi et al. 2013a, b). The biological indicators being used mostly are soil microbial biomass, their activities and respiration, enzymatic activity, mineralizable N, and its mineralizing rates (Paz-Ferreiro and Fu 2016). Muñoz-Rojas et al. (2016) reported that biological indicators (diversity and microbial activity in particular) are the most sensitive indicators to detect differences in soils of semi-arid areas. On the other hand, Stone et al. (2016), considered that leading soil quality indicators are those which are related to microbial biodiversity and ecological function (enzymes, respiration profiles induced by multiple substrates and functional genes).

After soil disturbance as a result of management interventions, the soils having greater biodiversity will be better able to maintain ecological processes (Cardoso et al. 2013). In this context, SSPs promote soil microbial diversity, presenting a structural complexity of vegetation similar to existing in natural ecosystems (Chará et al. 2015). Several investigations in the Gran Chaco used the microbial activity and density of groups of microorganisms such as cellulolytic, ammonifiers, and free-living N-fixing as biological indicators (Abril and Bucher 1999; González et al. 1999; Carranza et al. 2015). Other studies involved biological indicators related to the N biogeochemical cycle, including the N of microbial biomass, the net mineralization of N, the density of ammonifiers and nitrifiers microorganisms (Mazzarino et al. 1991; Anriquez et al. 2018). Longo et al. (2014) used the density and diversity of mycorrhizal fungus spores as a biological indicator. Anriquez et al. (2016) studied the quantity of glomalin produced by mycorrhizal fungi. On the other hand, various enzymatic activities (dehydrogenases, B-glucosidases, ureases, etc.) and the diversity of microbial communities were also studied as quality indicators to evaluate SSPs of the Chaco region (Anriquez et al. 2005, 2017; Silberman et al. 2016).

In the Gran Chaco, soil quality studies, focused on assessing the impact of SSPs on native forests, are still scarce. The inclusion of biological indicators is significant, as well as a systemic approach to achieve a better understanding of the functioning of soils.

14.4 Silvopastoral Systems in Native Forests

South America has the maximum area under agroforestry systems (Kumar et al. 2014). These systems are promoted as an economical, productive, and ecological alternative due to the environmental benefits of including trees in agroecosystems, such as C sequestration, reducing methane emissions, and the reduction of pressure in forests (Murgueitio et al. 2011). In the SSPs from temperate and subtropical areas of South America native forests with trees or livestock in production, or different forest species, are physically present in the same area. The SSPs provide a diversity of income, coming directly from wood, non-timber forest products, animals, or indirectly through the provision of ecosystem services such as shelters, soil conservation, nutrient balance, etc. Much of these forests belong to owners who have own cattle, which use forest grass as food and trees as a refuge for animals. Unfortunately, livestock generates soil compaction and hinders the natural regeneration processes of the forest. In other cases, "coppice" is practiced, a silvicultural system in which, every 15 years, zones of second-growth forests are cleared (Peri et al. 2016a, b, c).

In Brazil, the "Faxinais" were the first systems that combined forest and beef cattle, established in the mid-eighteenth century (Chang 1985), established mainly in native forests of Araucaria (*Araucaria angustifolia*). Recently, rural extension service and research institutions began to look for more innovative and sustainable agroforestry systems with the environment, integrating forestry with agriculture and livestock; problems such as animal welfare, deforestation of the native forest, rising costs of agricultural inputs, increasing land degradation, and rural depopulation were present (Dube et al. 2002; Meena et al. 2020a).

In Argentina, very assorted SSPs have been established, with different objectives and with both spatial and temporal varieties. In North-East Argentina, many farmers or companies seek to diversify their income and improve their economy; in South Argentina, they seek to care for livestock against strong winds and prevent soil erosion. Besides, it is considered advantageous because livestock provides income while wood production is carried out for a longer time. This variety of productive system reflects the integration of two components, the tree and the cattle, in the use of the land, intending to diversify products and income, avoiding economic and environmental risks, seeking sustainability in the production (Peri et al. 2017). In Corrientes and Misiones (Mesopotamia region), farmers have established SSPs with high production pines and C_4 pastures for livestock, seeking product diversification and increasing rents by area, compared to the traditional agricultural system. In this region, plantations of willows and poplars are concentrated for veneer, wood pulp, sawn wood, and biomass for bioenergy (Peri et al. 2016a, b, c).

In North Patagonia, 82,000 hectares land has been reforested with foreign conifers. Despite the state promotion of forest plantations for 40 years, only 10% of the regional potential was reached~~;~~ (Caballé et al. 2016). In any case, in Patagonia, a large part of farmers has been reluctant to adopt comprehensive silvopastoral management, perhaps due to the lack of evidence of the economic return of long-term benefits of ecosystem services (Peri et al. 2016a, b, c). The SSPs in the native forest of *Nothofagus antarctica* (“Ñire”) are also extensive in Patagonia and are an excellent economic, ecological, and social option (Peri et al. 2017). Successive thinning of secondary forests provides timber and non-timber forest products. In the Antarctic forest, livestock production is the primary source of the annual income of the SSPs.

South-West Chaco is a semi-arid region with little rainfall, so agricultural practices are limited, and the advance of the livestock frontier has been one of the leading causes of deforestation in the region (Hoyos et al. 2012). The process of intensification of livestock systems has led to the substitution of the native forest by exotic grasslands with the minimal representation of trees for the shading of livestock (Carranza and Ledesma 2005). In 2007, a new law for the protection of native forests was approved (National Law 26,331), considerably reducing deforestation in the Chaco. However, this new legislation has generated social conflict between society, which supports restrictions in favor of the ecosystem services of the native forest, and the productive sector. However, there are few well-preserved native forests in the semi-arid Chaco. Secondary and open forests are more frequent, more or less degraded (Zak et al. 2004; Conti et al. 2014)

In western Chaco, intensive grazing, extractive felling of trees, fences, or fire regimes have caused the formation of areas of shrubs and dense thickets, as well as degraded secondary forests. The SSPs in this region have been established in degraded savannas and mixed native forests to solve some of these problems (Kunst et al. 2006). More frequently, in this region, the mechanical treatment (RBI) is used, based on a selective disturbance of the vegetation, which attempts to maintain biodiversity, the natural regeneration of trees, soil conditions, and improve system productivity.

14.5 Land Rehabilitation Methods

The methods of land rehabilitation for SSPs from natural forests are based on the partial or total elimination of native vegetation, and the subsequent implantation of exotic herbaceous, or arboreal, and exotic herbaceous vegetation, respectively. In the Chaco Region, native vegetation is complex; it is composed of communities dominated by woody species (forests and bushes of shrubs or savannas). Woody vegetation (shrubs) gradually increased over the years with the consequent homogenization of the landscape, because of the intensive use of the land that resulted in the predominance of secondary forests with reduced diversity and decreased capacity of providing goods and services. Thus, the aptitude for livestock and timber management is low, since the herbaceous biomass is scarce, little dense or small, and the woody vegetation is abundant and thorny, making difficult the access of the cattle and the people. Livestock load in degraded native vegetation is minimal (30 ha UG^{-1}) (livestock unit) compared to native vegetation in right conditions (3–5 ha UG^{-1})

Fig. 14.1 Fachinales

(Albanesi et al. 2013a, b; Kunst et al. 2016). This situation is economically negative for livestock activities in areas with woody vegetation. This situation generates complex management, also frequent in other arid and sub-humid regions of the world since the regeneration of native savannas and grasslands would be difficult and expensive. The expansion of agricultural activity in the Chaco region increases the ecological characteristics of risk (semi-arid climate, more fragile soils, rehabilitation of lands with forest features), and constitutes a matter of technical and political importance for decision-making in the productive field and public policies; the territorial planning requires decision tools to evaluate the ecological, economic, and social aspects of agricultural expansion.

In the Chaco region on a "site" scale (1: 20,000), the soils and vegetation are distributed along a topographic gradient, from the "Alto" with thick textured soils and forest vegetation to the grassland or savanna in the "Bajo," with finer-textured floors and more development. The "parks" are located in the "Media Loma" (Kunst et al. 2003). The bushes or "Fachinales" (Fig. 14.1) are ubiquitous and have a different origin (lack of fire, overgrazing, etc.) that is defined by the position in the landscape; they currently constitute the most common physiognomy.

Rehabilitation practices for agriculture replaced native vegetation in savanna areas; subsequently, with the advance of the agricultural frontier, all the physiognomies of vegetation from the forest to the grassland, including shrubs or "Fachinales" were rehabilitated (and currently rehabilitated). The most used method is the total clearing with heavy machinery. The practice of rehabilitation affects the soil, depending on the method and the site to be rehabilitated. However, the decrease in SOM is common in all Chaco rehabilitations, due to total clearing exceeding 60% (Albanesi et al. 2013a, b; Kunst et al. 2014, 2016).

Between the models of clearing, we can find from the total clearing to the selective clearing, being the latter, possibly, a more sustainable model to intensify the production than the first; the selective clearing would best adapt to semi-arid environments like the Chaco, in social and ecological terms. The total clearing model is generally chosen by producers who have large areas of land since it is

Fig. 14.2 Silvopastoral system, native tree vegetation, and Gatton grassland

fast and leaves the surface without remains that hinder animal transit. In general, the treatments used are mechanical, with the subsequent use of fire to remove biomass and then spread the ashes employing tillage. These treatments are very aggressive for soil and vegetation.

In the Argentine Chaco, currently, SSPs are designed in degraded secondary forests, usually mechanized. Manual or mechanical selective clearing, generally used by small and medium producers, eliminates the shrub component and diseased and dead trees, leaving all or part of the tree component to provide a protective cover to the soil, pastures, and animals. Selective clearing achieves a certain percentage of shade on the surface, which tends to optimize pasture productivity and conserve the soil and biodiversity. This partial clearing is one of the best practices for more efficient use of the land and to improve the conditions of livestock production.

Generally, a practice of selective clearing is used called RBI, which consists of passing a “roller” (Figs. 14.2, 14.3, 14.4, 14.5 and 14.6) pulled by tractor or bulldozer that “crushes” the “Fachinal” and leaves the woody ones of greater diameter and can be accompanied by sowing subtropical grasses (Fig. 14.2). The result is a “park” composed of woody and grass (Kunst et al. 2016). The RBI aims to integrate livestock and forestry. This practice reduces the low woody layer (<3 m high, mainly shrubs) through a “roller chopper,” an iron drum of diameter = 1.4 meter (m) and width = 2.5 m, 3000 kilograms (kg), full of water, armed with blades, usually pulled by a 4-wheel articulated tractor or by a D4 Caterpillar excavator (Fig. 14.3). RBI is a selective mechanical disturbance of the shrub layer, which aims to generate a tree-herbaceous vegetation structure, more suitable for livestock activities. Simultaneously, productive exotic herbaceous species such as *Panicum maximum* cv Gatton panic (Gatton grass) are sown (Fig. 14.2), getting an increase in forage production (Kunst et al. 2014). This practice is recommended in lands within the green and yellow category according to the territorial planning of Argentina (Law No. 26,331; Law No. 6942).

The RBI significantly increases livestock receptivity and leaves a large amount of woody debris and leaves on the ground, and removes it slightly with the blades, leaving its rough surface, thereby decreasing the loss of water through runoff; the remaining deciduous trees contribute to the soil a large number of leaves, branches,

Fig. 14.3 Roller pulled by a tractor

Fig. 14.4 Small roller for small surfaces can be pulled by tractor or animal traction

fruits, and roots, a substrate for mineralization (Kunst et al. 2003). The operator must be very well trained to apply the disturbance with the lowest possible intensity, that is, leaving as many trees of different ages to ensure the natural regeneration of the forest and not "pampeanizar" the ecosystem. Controlled grazing is recommended,

Fig. 14.5 Front roller, with hydraulic traction

Fig. 14.6 Self-propelled roller recently developed by INTA

not grazing flush to maintain a good grass cover that intercepts the radiation and thus restricts the growth of shrubs.

The environment achieved with these treatments has more advantages than the total clearings since the shade of the trees attenuates the adverse effects of the climate, such as frost and drought; the pastures retain their forage value in the dry season, favoring the weight gain of animals in critical months. When the "roller" is used with crushing fins, the fine woody material is chopped, and its incorporation into the soil is facilitated, without the need to burn; at the same time, it causes a superficial soil removal that is suitable for the germination of pasture seeds.

Rolling and planting of megathermic pastures increase the supply of forage by 300–600% (Kunst et al. 2008) with an average yield of 3500–11,500 kg dry materials ha^{-1} (Kunst et al. 2014). It does not have a significant effect on the tree cover of the dominant Chaco species; besides, it maintains the woody biodiversity of greater forest importance (Silberman et al. 2015, 2016) and the diversity of birds (Albanesi et al. 2013a, b). Also, it improves the weight gain attributed to animal welfare generated by the shade of trees, and reduces the stress caused by high temperatures (Navas Panadero 2010). It constitutes an attractive alternative to the threats towards biodiversity perceived by society, the demands towards the conservation of forests and other natural ecosystems, which have multiplied since the 1980s (Peri et al. 2006).

It is necessary to apply the disturbance every five years or so, to control the reinvasion of the woody shrubs. The application of RBI more frequently than indicated above is counterproductive, since it activates the growth of woody shrubs. The most significant possible number of trees should be left, since in areas without them, the SOM is significantly lower. Besides, grazing pressure should be monitored, since a high loading rate will result in decreases in the SOM (although lower than in the case of total clearing).

14.6 Effects of Low-Intensity Roller-Chopping on Soil

It is very crucial for a better relationship among the different components of SSP (Smith et al. 2012) and the soil is the most relevant because it sustains the productivity and maintains the sustainability of agroecosystem. Soil organic matter is the main component of a minimum set of data required to determine the soil quality (Albanesi 2008).

Research in SSPs in Latin America has increased considerably since 1983 (Soler et al. 2015). However, several aspects such as soil ecology remain poorly understood. A complex vision is required for the understanding of the soil system and the restoration of biological processes, fundamental aspects to guarantee food and environmental safety. The conversion of the native forest to the silvopastoral system is an important change in the ecosystem in which both vegetation and fauna are modified. Previous studies have determined that tree cover of dominant species, tree, and bird diversity is preserved (Gómez and Navall 2008; Albanesi et al. 2013a).

Our knowledge of the impact on soil health, closely coupled with the concept of soil quality, is limited (Lehman et al. 2015). The evaluation of soil quality is generally achieved through the direct measurement of a set of biological, chemical, and physical properties and processes of the soil, which have the greatest sensitivity to changes in soil function (Lehman et al. 2015). Due to its critical role in many soil properties and processes, provide an integrative concept to understand and promote soil health and quality (Albanesi 2015). Conversions from natural vegetation areas to production systems significantly reduce SOM, and the most severe effect occurs when forests and grasslands are replaced by field crops (Albanesi et al. 2013a; Kunst et al. 2014, 2016). The RBI has minimal impact on the diversity of soil microbial communities. One year after implementing RBI, the diversity of bacteria is altered due to changes in the availability of resources (water and C input). These changes are reversible, since at five years there is a restoration of most bacterial groups (Silberman et al. 2016).

14.6.1 Effect of Low-Intensity Roller-Chopping on Soil Processes

Upland Sites (UP) In secondary forests treated with RBI and rotational grazing, soil bulk density (SBD) was not affected even after 5 years of the initial soil disturbance (Table 14.1) (Albanesi et al. 2013a, b). This means that the flow of water and air in the soil was maintained. The TOC, POC, Microbial biomass carbon (MBC), and MBC/TOC were not modified in the plots (Table 14.1).

These results are due to the leftovers branches and leaves that were contributed and crushed by the roller chopper. Probably, the roots of Gatton grass decompose and enter into the soil quickly. In any case, TOC, POC, and MBC/TOC decreased due to grazing, including rotational grazing, possibly because the animals removed plant material in their path (Tadesse et al. 2002). However, the rate of TN increased, possibly through feces, as has happened in other SSPs (Nyakatawa et al. 2011).

Table 14.1 Soil properties after 5 years of rolled-chopped applied

Particular	SBD (g soil cm^{-3})	TOC (g C kg^{-1} soil)	POC (g C kg^{-1} soil)	TN (g N kg^{-1} soil)	MBC (ug C g^{-1} soil)	MBC/ TOC (%)	qCO$_2$
Control	0.84 a^1	30.10 b	25.37 b	2.24 a	226.07b	0.58 a	0.26 ab
Roller-chopped	0.84 a	28.77 b	24.14 b	2.72 a	167.63 b	0.55 a	0.28 ab
Roller-chopped plus cattle grazing	0.87 a	22.94 a	18.91 a	2.11 a	91.84 a	0.37 a	0.46 b

TOC total organic carbon, *POC* particulate organic carbon, *SBD* soil bulk density, *MBC* microbial biomass carbon, *TN* total nitrogen, ratio MBC/TOC, *qCO$_2$* microbial metabolic quotient at a depth 0–15 cm. Mean values are reported. Values in the same column with different letters differ significantly ($p < 0.05$) according to the Duncan's test

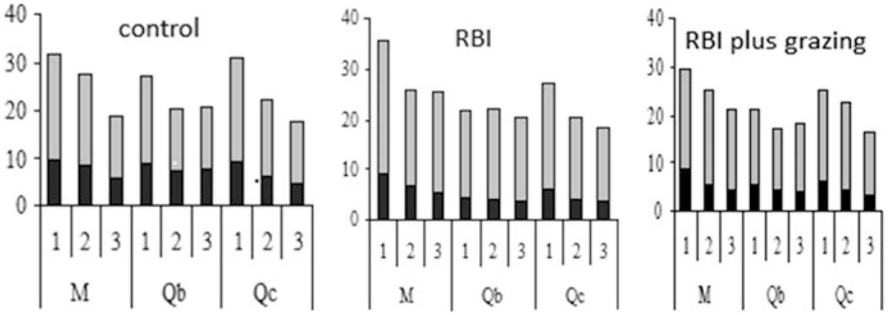

Fig. 14.7 Soil organic carbon (black bars) and particulate organic carbon (gray bars) in g C kg^{-1} of dry soil at a depth = 0–15 cm, average 2007–2012. 'La María' Experimental Ranch, INTA Santiago del Estero. RBI: two roller-chopper passes plus seeding of Gatton grass, RBI plus grazing, Control: no treatment. (1) 0.50 m from the tree bole; (2) crown center, and (3) crown border. *Qb* quebracho blanco, *Qc* quebracho colorado, *M* mistol

In the RBI plots, the tree cover affected significantly the C cycle. Possibly due to a gradient of accumulation of organic waste; SOM, TOC, and POC decreased as the sampling distance to the tree trunk increased (Fig. 14.7). This means that the tree cover is essential in the SSP, and the treetops must touch or overlap, since under the cover there is a more significant contribution of C from organic leftovers. In addition, the effect of the tree depends on each forest species; *Ziziphus mistol* (Mistol) provides 16–64% more organic waste than other species; also, the TOC was higher in Mistol.

The microbial metabolic ratio (qCO_2) increased, reflecting stress and decreasing the efficiency of water use by the soil microbiome (Table 14.1). The RBI generally leaves most of the trees standing; this can cause a more enormous amount of the fast mineralization C fractions, an increase in the mineralization rate (kc), and microbial activity that is responsible for initial degradation of SOM. Also, the dehydrogenase activity (Dh-asa) was high, confirming this finding (Table 14.2).

Midland Site (MD) The RBI and the seeding of Gatton grass caused a decrease in C reserves available for short-term mineralization (C_0), while the mineralization rate (kc) increased (Table 14.2). The TOC and POC for rapid mineralization are low in the central region. This suggests that, on this site, the grazing of exotic species in an SSP should be carefully planned, because a small magnitude of C_0 and a fast rate of mineralization can accelerate the TOC loss.

14.6.2 Genetic Diversity in Microbial Communities

The research that we have carried out over 5 years in the central Chaco (humid) and the Western Chaco (semi-arid) suggests that the RBI affects the microbial communities of the soil as a function of the weather. In the western sub-humid

Table 14.2 Potential mineralizable Carbon (C_0), mineralization rate (kc), and dehydrogenase activity (Dh-asa) at 0–15 cm soil depth in a roller-chopper experiment between 1999 and 2003 (Roller-chopped applied in 2000)

	C_0 (mg C kg^{-1} soil)			kc (mg C kg^{-1} soil day^{-1})			Dh-asa (mg TPF kg^{-1} soil h^{-1})		
	Ecological sites								
	UP	MD	LL	UP	MD	LL	UP	MD	LL
Control	384.4	344.2	338.7	0.040	0.054	0.019	96.8	103.9	119.3
RBI	454.1	290.1	386.7	0.027	0.064	0.025	96.1	95.2	134.2

Mineralizable potential carbon (C_0), Mineralization rate (kc), and dehydrogenase activity (Dh-asa) at 0–15 cm soil depth. 'La María' Experimental Ranch INTA Santiago del Estero. Ecological sites: *UP* upland, *MD* midland, *LL* lowland. Treatments: Control, no treatment; RBI: low-intensity roller-chopping with seeding of Gatton grass

Chaco, results indicated that RBI alters the composition of soil bacteria, determined by the Denaturing Gradient Gel Electrophoresis (rDNA 16S PCR-DGGE), by modifying their habitat. However, after the disturbance, the initial microbial composition is restored at 5 years (Kunst et al. 2014). The same trend seems to exist in the central Chaco; however, the distance of the fingerprint profiles between the plots and the controls treated with RBI is shorter indicating the minor changes in communities (Fig. 14.8).

This is in line with other studies that report the relationship between changes in plant communities and microbial communities (Lupatini et al. 2013). The crushing and contribution of residues of shrubby vegetation by RBI, modify the soil microbial communities one year after the treatment. This supposes a vital contribution of C to the ground. According to Ng et al. (2014), the relationship between the composition of the C and the structure of the soil microbiome is direct.

On the other hand, the fungal communities of the soil are distributed according to the type of soil and climate, as confirmed by the ADNr 18S T-RFLP technique (Fig. 14.9). In any case, RBI modifies fungal communities, being more evident in the Western Chaco than in the central Chaco, due to greater incorporation of woody waste, the substrate of some fungal communities (Ng et al. 2014).

This means that native microbial communities better tolerate environmental changes, the RBI generates a low impact, and the RBI does not alter the processes of biogeochemical cycles carried out by soil communities.

14.6.3 Functional Diversity of Microbial Communities

Physiologic profiles gathered using BIOLOG MicroEcoPlate from 31 different C sources show significant differences between the western and central Chaco region (Fig. 14.10).

The RBI in the western Chaco shows higher values of diversity indices (Table 14.3), consequently more enormous metabolic potential and functional diversity due to a site effect due to higher soil moisture content (Albanesi et al. 2013a, b).

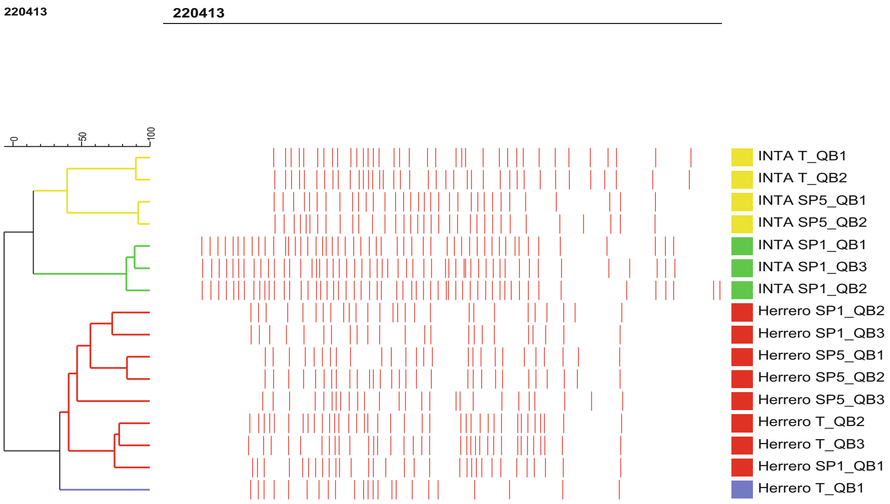

Fig. 14.8 Dendrogram built with Bionumerics software based on 16S-DGGE rDNA profiles. *Herrero* sub-humid environment, *INTA* semi-arid environment, *T* control, *SP1* one-year RBI, *SP5* 5-year RBI, *QB* Quebracho blanco (*Aspidosperma quebracho blanco*)

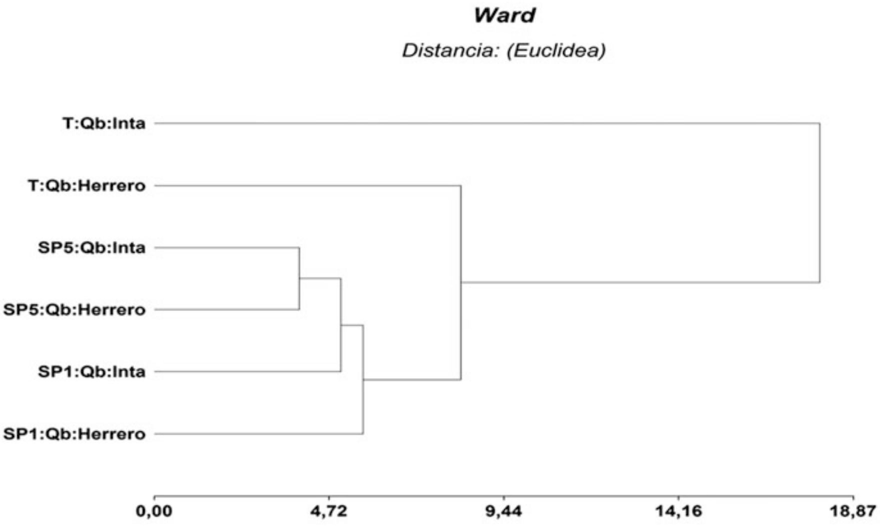

Fig. 14.9 Dendrogram constructed based on 18S-TRFLP (Terminal restriction fragment length polymorphism) rDNA profiles. *Herrero* sub-humid environment, *INTA* semi-arid environment, *T* control, *SP1* one-year RBI, *SP5* 5-year RBI, *QB* Quebracho Blanco

The RBI involves the passage of a roller that could compact and modify various soil functions. The apparent density is the basic but critical physical soil property that is strongly correlated with the quality of the soil and the productivity of the site

(Suuster et al. 2011). Twenty years of experience showed that the RBI does not compact the soil because it keeps the woody root system intact and the woody residues are not exported from the system but are kept on the ground (Albanesi et al. 2013b; Kunst et al. 2016).

The SSPs of the Chaco Region have a great potential to sequester C to the soil, but we have to be careful because a large part of C is sequestered in labile forms, and if improper handling is done for the region (e.g., overgrazing), it will rapidly release to the atmosphere as CO_2 (Albanesi et al. 2013b; Silberman et al. 2015, 2016; Kunst et al. 2016; Sanchez et al. 2019).

According to our experience and based on scientific information obtained for more than 20 years, we can express that the SSPs are favorable for the region since they allow the increase in meat production while maintaining the base resources, including the soil.

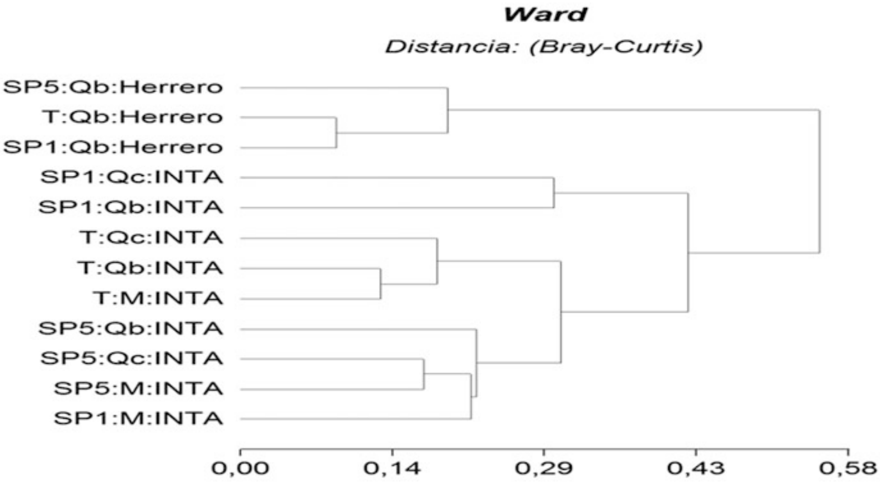

Fig. 14.10 Dendrogram constructed based on physiological profiles at the community level (obtained with BIOLOG MicroEcoplate) using the Ward method. *Herrero* sub-humid environment, *INTA* semi-arid environment, *T* control, *SP1* one-year RBI, *SP5* 5-year RBI, *Qb* quebracho blanco, *Qc* quebracho colorado (*Schinopsis lorentzii*), *M* mistol

Table 14.3 Average values of diversity indices for the different treatments at each site

Treatment	Site	Richness		Shannon		Simpson	
SP1	Herrero	17.17	A	2.68	b	0.02	ab
SP5	Herrero	11.67	A	2.28	a	0.01	a
T	Herrero	17.67	B	2.74	b	0.02	ab
SP1	INTA	15.75	B	2.61	b	0.03	bc
SP5	INTA	23.75	B	2.97	c	0.04	cd
T	INTA	23.75	B	2.92	c	0.05	d

Herrero sub-humid environment, *INTA* semi-arid environment, *T* control, *SP1* one-year RBI, *SP5* 5-year RBI. Different letters indicate significant differences ($p < 0.05$)

14.7 Effects of Plant Cover on Soil

The importance of woody plants in SSPs of semi-arid regions is related to the reduction of loss of water and nutrients (Abule et al. 2005; Silva et al. 2011); the trees contribute a higher proportion of stabilized C in the soil (Lorenz and Lal 2014). On the other hand, the symbiotic microbial community can affect the nutrition of trees, and therefore their physical state. Previous studies show that the distribution of rainfall along the canopy can modify the interrelation between symbiotic microorganisms of the soil and the roots of trees, changing soil properties. In fact, the structure of the canopy can modify the signaling pathways between the tree and its microbial partners (such as moisture or soil chemistry), by dividing the precipitation in two ways: through the dripping of water from the canopy to the ground, and flow through the trunk of the tree, with water flow and solutes that it drags, creating a defined area of infiltration (Rosier et al. 2015).

The residues of different tree species contribute differentially to the fractions of SOM since the type and composition of the mulch significantly affect the stability of the SOM (Kovaleva and Kovalev 2009; Abril et al. 2013); such as Quebracho Blanco leaves are resistant to degradation resulting in more humifiable residue (Torres et al. 2005; Meena et al. 2020) compared to *Prosopis flexuosa* (Griseb) and *Geoffroea decorticans* (Gilles ex Hook and Arn.), whose leaflets are easily degradable and remain on the soil surface for short periods (Abril et al. 2013).

It has been shown that the effect of the tree component on different edaphic parameters depends on the tree species in question. Silberman et al. (2015) evaluated the impact of the conversion of semi-arid Chaco native forest to SSPs on soil C fractions (TOC and POC), soil nitrogen (TN), and soil respiration (RE) (Table 14.4). The treatment was RBI and the Native Forest as control. The various cover factors were the soil without tree cover, the soil under cover of Quebracho Blanco, and the soil under cover of Mistol. The RBI maintained C stocks of soil and native tree cover was crucial in preserving SOM and microbial activity. Soil C, soil N, and soil microbial activity was a function of tree cover; TOC, POC, NT, and RE were lower in soil without tree cover, intermediate under cover of Quebracho Blanco, and higher under the canopy of Mistol because of the increased supply of litter by these latter species.

Also, in bare soil and soil under Quebracho Blanco, Mistol, and Quebracho colorado, Anriquez et al. (2016) evaluated TOC, MBC, POC, MBC/TOC, POC/TOC, total glomalin (GT), and easily removable glomalin (GFE) (Table 14.5 and Fig. 14.11). In areas without tree coverage, a significant decrease of all the parameters evaluated was observed, and a significant increase of these parameters was shown under the tree cover, more patently under cover of the Mistol. The average MBC/TOC was 2%, suggesting that the soil microbiota has low metabolic efficiency, characteristic of semi-arid ecosystems.

Also, each species of grass can characterize different effects in some soil parameters. Hawkes et al. (2005) indicated that nitrification process increases in the presence of exotic grasses because the microorganisms involved in these processes can obtain a more substantial fraction of mineral N when they are associated

Table 14.4 Mean values and standard errors of TOC, POC, RE, TN, and CN ratio for different tree covers, soil treatments, and years

Cobertura	Año	Trata miento	TOC (g C kg^{-1} suelo)		POC (g C kg^{-1} suelo)		TN (g C kg^{-1} suelo)		RE (μg C −CO2 g^{-1} suelo dia^{-1})		C:N	
D	2007	RBI	13 ± 1.2	GHI	9 ± 1.8	FG	1.8 ± 0.2	DEF	7 ± 1.2	G	7 ± 1	F
		T	11 ± 1.4	I	9 ± 1.4	EFG	1.2 ± 0.2	FG	9 ± 0.5	FG	9 ± 1.6	EF
	2009	RBI	10 ± 1.3	I	8 ± 1.3	G	0.7 ± 0.1	GH	18 ± 1.6	E	14 ± 2.6	CD
		T	13 ± 1.4	GHI	10 ± 1.4	EFG	0.8 ± 0.1	GH	26 ± 7.4	D	17 ± 2.8	BC
	2011	RBI	15 ± 2.8	FGH	13 ± 2.9	E	0.6 ± 0.1	H	15 ± 5.5	EF	5 ± 3.6	A
		T	12 ± 2.4	HI	11 ± 2.4	EFG	0.6 ± 0.1	H	12 ± 2.8	EFG	19 ± 2.6	B
M	2007	RBI	24 ± 4.6	CD	20 ± 4.9	CD	2.7 ± 0.6	AB	8 ± 1.91	FG	9 ± 2.1	EF
		T	16 ± 1.8	FGH	13 ± 1.9	EF	1.7 ± 0.2	DEF	11 ± 1.3	EFG	9 ± 1.1	EF
	2009	RBI	34 ± 2.8	A	27 ± 2.8	AB	2.1 ± 0.5	CDE	35 ± 4.6	BC	16 ± 3.5	C
		T	28 ± 3.6	B	20 ± 4.5	CD	2.2 ± 0.4	BCD	35 ± 9.6	B	13 ± 2.4	D
	2011	RBI	27 ± 4.6	BC	24 ± 4.2	BC	1.4 ± 0.3	F	34 ± 3.3	BC	20 ± 3.8	B
		T	34 ± 6.8	A	29 ± 6.8	A	3.0 ± 0.6	A	28 ± 3.0	CD	11 ± 2.0	E
Qb	2007	RBI	18 ± 2.8	EF	13 ± 3.4	E	2.1 ± 0.5	CDE	8 ± 1.3	FG	9 ± 2.2	EF
		T	17 ± 3.0	F	13 ± 3.9	E	2.0 ± 0.2	CDE	12 ± 1.0	EFG	9 ± 1.0	EF
	2009	RBI	24 ± 3.3	CD	19 ± 3.4	D	1.7 ± 0.3	DEF	26 ± 3.9	D	14 ± 2.5	CD
		T	16 ± 1.1	FG	10 ± 2.4	EFG	2.4 ± 0.8	BC	44 ± 8.0	A	7 ± 2.2	F
	2011	RBI	23 ± 3.4	D	20 ± 3.1	CD	1.4 ± 0.3	F	34 ± 8.4	BC	16 ± 3.0	C
		T	22 ± 4.3	DE	19 ± 3.9	D	1.6 ± 0.4	EF	30 ± 4.9	BCD	14 ± 3.2	EF

T native forest, *RBI* silvopastoral system with low-intensity roller-chopping and planting of Gatton grass, *D* soil without tree cover, *Qb* soil under cover of Quebracho Blanco, and *M* soil under cover of mistol. Means with the same letter are not significantly different ($p > 0.05$)

Table 14.5 Microbial biomass carbon (MBC), total organic carbon (TOC), particulate organic carbon (POC), ratio MBC/TOC and POC/TOC in soil under the coverage of Quebracho colorado (Qc), Quebracho blanco (Qb), Mistol (M), and without cover (D)

Canopy	TOC (g C kg^{-1})	POC (g C kg^{-1})	MBC (ug C g $soil^{-1}$)	POC/ TOC	MBC/TOC (%)
D	10.18 a	7.73 a	237.19 a	0.76 a	2.35 a
Qc	23.78 b	20.65 b	461.78 a	0.87 a	2.00 a
Qb	23.83 b	20.55 b	445.46 a	0.87 a	1.83 a
M	31.18 b	26.65 b	379.16 a	0.83 a	1.09 a

Values in the same column with different letters differ significantly ($p < 0.05$)

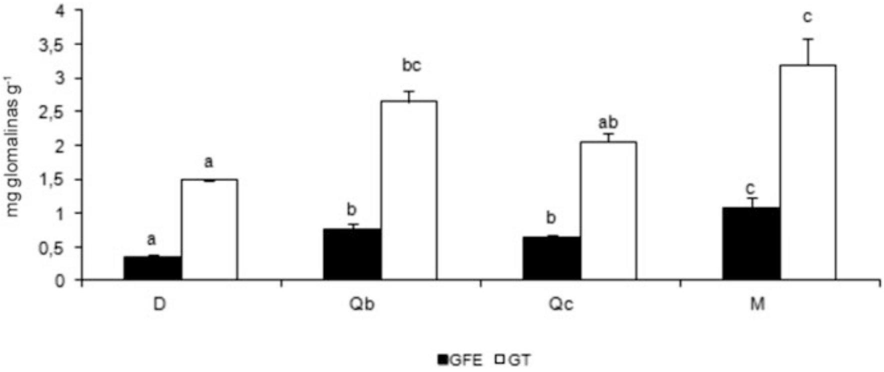

Fig. 14.11 Mean values of easily removable Glomalin (GFE) and total Glomalin (GT) expressed in mg g^{-1} soil under the coverage of Quebracho colorado (Qc), Quebracho Blanco (Qb), Mistol (M), and bare soil (D). Different letters indicate statistically significant differences (Duncan $\alpha = 0.05$)

with them. Patra et al. (2005) recorded increases in the size of nitrifying populations induced by grazing; this could increase root/shoot allocation, root exudation, possibly primary production, and therefore the availability of nutrients and labile organic substrates.

Albanesi et al. (2013b) showed that tree cover in SSPs in this region has a significant effect on soil properties; they reported that organic soil carbon (TOC) increases inversely to the distance to the shaft of the trees, by an accumulation gradient of mulch; therefore they advise leaving as many trees as possible, trying to get the treetops to touch each other.

Anriquez et al. (2018) showed that the vegetation cover and grazing are the main determining factors of the variations of the soil microbial communities involved in N cycling; to maintain the diversity of tree species and the inclusion of pastures ensure more considerable heterogeneity of habitat, generating greater microbial diversity, promoting the sustainability of the soil resource. The shade of the trees and the cover of the grass are imperative in the conservation of humidity and the moderation of the soil temperature, which favors the increase in the biomass of microorganisms.

14.8 Effects of Grazing on Soil

14.8.1 Effects of Grazing on Soil Organic Carbon

Grazing is capable of modifying the soil ability to sequester C (Cui et al. 2005) depending on the climate (Abdalla et al. 2018), grass species (C_3 or C_4), and soil texture (McSherry and Ritchie 2013). Several researchers reported that soil C decreases upon grazing (Ciais et al. 2010; Powlson et al. 2011; Deng et al. 2017). This effect is more severe in water-limited environments (An and Li 2015), meaning that the effects of grazing on the soil organic carbon are more prevalent in arid and semi-arid areas (Raiesi and Riahi 2014); grazing can reduce C inputs from aboveground and underground biomass in regions where the temperature and evapotranspiration are high (Abdalla et al. 2018; Meena et al. 2018), such as the Chaco (Morello 2012). Wang et al. (2014) reported that grazing exclusion is capable of increasing organic carbon in the soil. These results are supported in Xiong et al. (2016) who in turn reported that these benefits are more in humid areas than in arid areas. However, other authors reported that grazing increases the underground biomass of pastures so it could increase the TOC (López-Mársico et al. 2015), especially when is low stocking rate (Ferreiro-Domínguez et al. 2016).

Research conducted in Western Chaco suggested that the significant effects of grazing on TOC and POC are detectable at 5 years post-RBI (Figs. 14.12 and 14.13) (Albanesi et al. 2013a, b). The decrease in TOC due to grazing is consistent with several authors, who reported that grazing lowers soil C, compared to land without grazing (Ciais et al. 2010; Powlson et al. 2011; Wang et al. 2014; Xiong et al. 2016; Deng et al. 2017). Raiesi and Riahi (2014) reported that the effects of grazing on the TOC are particularly evident in arid and semi-arid areas where the resources are limited, mainly water and low litter. Banegas et al. (2015) reported that grazing in the semi-arid Chaco accelerates litter decomposition for the short term. Abdalla et al. (2018) reported that in warm-dry climatic zones, the effects of grazing are perceived on time scales higher than 20 years in most cases. However, these same authors reported that it is possible to find differences between 2 and 6 years in some cases. Changes in TOC concentration in a short time are probably due to fact that in the soils of the Chaco region, much of the C (60–70%) is labile (POC) (Albanesi et al. 2013a, b; Silberman et al. 2015; Anriquez et al. 2016; Kunst et al. 2016), and therefore, susceptible to management practices (Duval et al. 2013; Singh et al. 2016). Peri et al. (2017) suggested that, in the Chaco region, livestock systems and agroecosystems can be an excellent option to sequester C and access the commercial activity for the producer. Therefore, the TOC in SSP should continue to be monitored, since the balance in the TOC in the SSPs would be reached at 120 years (Poeplau and Don 2015); the researches in the semi-arid Chaco are still scarce, especially the studies at regional level (Peri et al. 2016a, b, c).

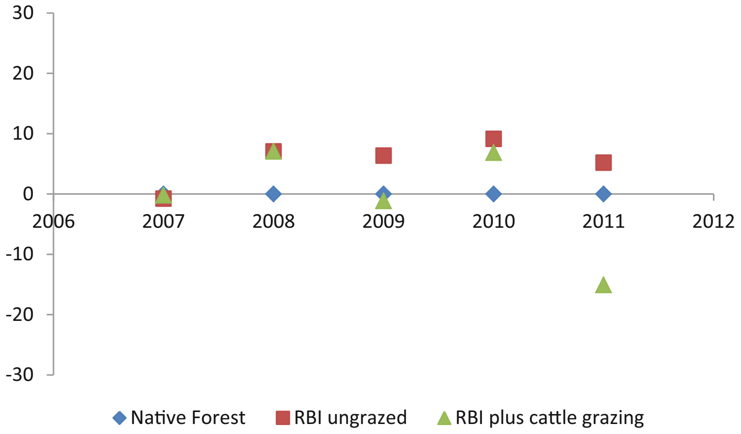

Fig. 14.12 Changes (%) in soil organic carbon in a "low-intensity roller-chopping" (RBI) experiment (2006–2011). INTA Santiago del Estero Experimental Research Station, Francisco Cantos Ranch

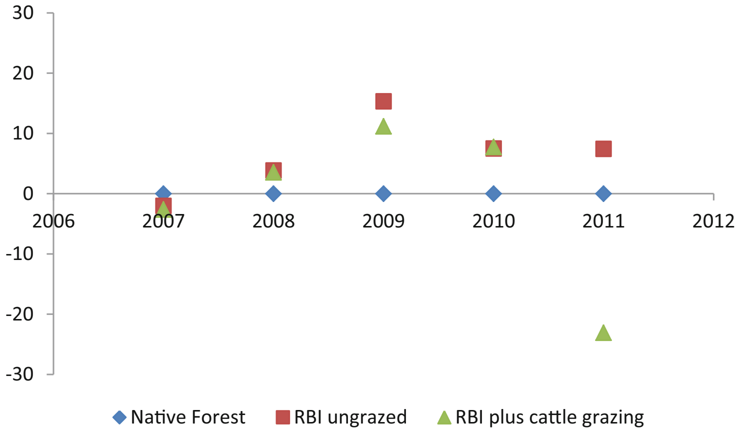

Fig. 14.13 Change (%) in particulate organic carbon in a "low-intensity roller-chopping" (RBI) experiment (2006–2011). INTA Santiago del Estero Experimental Research Station, Francisco Cantos Ranch

14.8.2 Effect of Grazing on Soil Nitrogen

Similar to TOC, soil nitrogen (N) can be modified by grazing activities. However, the magnitude and direction of changes in soil N upon grazing are context-dependent. Sarabia et al. (2020) reported that grazed SSPs improve the N cycle in coincidence with Peri et al. (2019) who reported that good management practices in semi-arid areas, such as low-impact grazing, can maintain or even increase soil N reserves. On the other hand, Carrera et al. (2003) reported that it is possible that grazing in arid ecosystems indirectly affects the soil by modifying the vegetation cover, whose changes are detectable in the short term (5 years) (Ma et al. 2016).

Researches conducted in western Chaco suggested that grazing would not have effects on soil N in the short term (Fig. 14.14) (Albanesi et al. 2013a, b; Kunst et al. 2016). Berg et al. (1997) found no significant differences in the concentration of N in the soil when comparing pastures moderately grazed by cattle *vs* ungrazed pastures for 50 years (closures) in sandy soils. Even though SSPs involve an export of N from the systems through the sale of livestock, it has been reported that SSPs increase the abundance of free-living N-fixing bacteria (Anriquez et al. 2018). The inputs of N through the biological N fixation would compensate for the outputs of N (meat). These conclusions show that grazing in SSPs enabled by RBI maintains N reserves in the short term. This is extremely important in the ecosystems of the Chaco region since the N of the soil is an indicator of sustainability in environments with climatic restrictions due to low rainfall (Peri et al. 2019).

14.9 Public Policies to Promote Forest Management with Integrated Livestock

14.9.1 Forest Law in Argentina

In 2007, in a complex socio-economic and environmental context (Aguiar et al. 2018), Law 26,331 was passed. This law defines the minimum environmental protection budget for the conservation, restoration, exploitation, and sustainable management of native forests. It promotes the environmental services of native forests and establishes the criteria for the distribution of funds for such environmental services. This national law mandated the provincial states to carry out land use

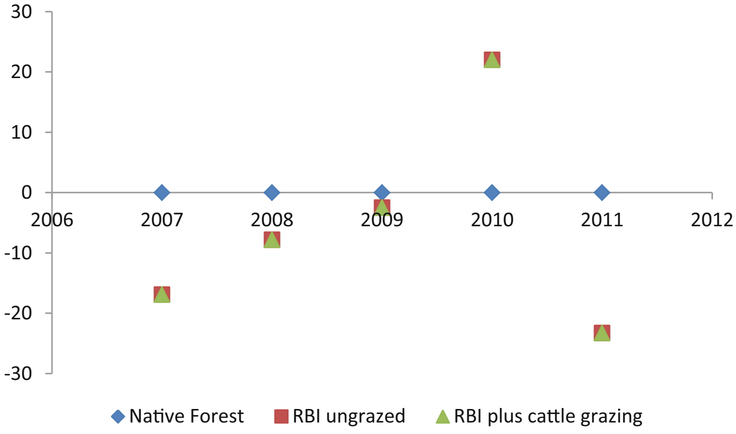

Fig. 14.14 Change (%) in soil nitrogen in a “low-intensity roller-chopping” (RBI) experiment (2006–2011). INTA Santiago del Estero Experimental Research Station, Francisco Cantos Ranch

planning, that is to say, that each provincial state must categorize its forests according to their conservation value:

- Category I (red): Areas of high ecological value, to preserve and not transform; areas to be conserved as forests indefinitely, given their location concerning natural reserves, biological importance, connectivity and/or protection of hydrographic basins, although they may be areas of scientific research or the habitat of indigenous communities.
- Category II (yellow): Areas of average ecological value, with some degradation, but may have high conservation value if restoration activities are carried out, according to the jurisdictional authority; sustainable use, scientific research, collection, and tourism activities can be developed.
- Category III (green): Areas of low preservation value, which can be partially or totally transformed, within the guidelines established by law.

Positive aspects of the law	Challenges to solve
• The unpublished instrument in Argentine legislation (Aguiar et al. 2018) • Restriction to land clearing in yellow and red areas (Art. 14) • Creation of the National Fund for the Enrichment and Conservation of Native Forests (Art. 30) • From the regulation of the law until 2018, 4500 forest management and conservation plans were financed • Condemnation of Juan José Karlen to 6 months' imprisonment for the illegal clearance of 11,875 hectares of native forests (fiscalpenalesalta.gob.ar) • Creation of the National Registry of Offenders (Art. 27°)	• The budget effectively allocated to enrichment and conservation of forests is less than that determined by Law 26,331 • The law provides for citizen participation in the territorial planning of native forests, although in many provinces it was variable and even for some, citizen participation is not documented (Aguiar et al. 2018) and in other cases, the opinion of citizens did not have implications (Seghezzo et al. 2011) • The law highlighted intense land tenure conflicts, which made territorial planning difficult, especially in the Chaco Region (Peri et al. 2017; Aguiar et al. 2018) • There is a scientific knowledge gap that hindered the land use planning since some provinces did not even have a cartographic base (Aguiar et al. 2018) • Criteria for determining the different conservation categories were very variable. Forests with similar characteristics received different categories in neighboring provinces (García Collazo et al. 2013) • The misuse of this term "silvopastoral" generated intense controversies since under this term diverse systems integrated by woody, herbaceous vegetation and animals that do not necessarily imply the conservation of forests are included (Aguiar et al. 2018) • Control of illegal land clearing was insufficient (Volante and Seghezzo 2018) • Only a few provinces contribute to the national registry of offenders, even when the clearing progresses in them

14.9.2 Law 26,331 had the Desired Effect

Nolte et al. (2017) reported that large-scale deforestation in the Chaco ecoregion (Argentina) was significantly reduced and affirm that this fact is a consequence of the application of the Forest Law. However, this paper received much criticism from researchers and academics in the region. Volante and Seghezzo (2018) made methodological objections to the paper by Nolte et al. (2017), among which the declining trends in deforestation began before the enactment of Law 26,331 and land use planning. It does not include the province of Formosa that presented high rates of deforestation in recent years even after the enforcement of Law 26,331, and finally that the total deforested area was considered in the evaluation and was not discriminated by category according to its conservation value.

Although there has been a decrease in deforestation in recent years, this cannot be directly attributed to effective compliance with the forest law. It is necessary to recognize the leading role of indigenous communities, small farmers, and those in reducing agricultural expansion (Volante and Seghezzo 2018). Law 26,331 prohibits land clearing in red and yellow areas, so it is expected that the variation in the surface clearing in these areas before and after the implementation of the law in the provinces is zero. The fact that it has increased the deforested area in red and yellow areas is clear evidence that the law did not have effective compliance (Volante and Seghezzo 2018). Despite reductions in deforestation rates, Sans et al. (2018) suggested that the zoning policy in Santiago del Estero was not effective enough since deforestation occurred in prohibited areas and generally exceeded the level of deforestation allowed. Lende (2018) states that clandestine deforestation is a problem present in several provinces of northern Argentina (Santiago del Estero, Salta, Chaco, and Formosa). It is clear that alternative coercive mechanisms are needed (for example, more severe penalties for criminals) and greater efforts to detect illegal deforestation to improve the effectiveness of the Forest Law (Sans et al. 2018). However, it seems that there is no political will to do so (Pérez Esquivel Com. Pers.). Although "Fines are applied to violators of the Forest Law, but they are not sufficient to discourage crime; in many cases, the complicity of officials in the violation of legal regulations is clear" (Greepeace 2017).

14.9.3 Forest Management Incorporating Livestock

The argentine agencies that promote conservation (Ministry of Environment and Sustainable Development) and production (Ministry of Agribusiness), established in 2015 some general guidelines for Forest Management that Incorporates Livestock (FMIL) in areas with sustainable management permit (Category II of Law 26,331) (Peri et al. 2017).

One of the purposes of the FMIL is to clarify the controversies generated by the term "silvopastoral" since it implies productive activities that include woody, herbaceous, and animal vegetation although this does not necessarily mean the conservation of forests (Aguiar et al. 2018). In this sense, the land use planning of province of Santiago del Estero names the following definition:

> The SSPs are a modality of integrated management of natural resources aimed at maintaining and improving interactions between plants, animal, edaphic, water, social and legal components. SSPs are a means of multiple uses of forests and other natural ecosystems that allow diversifying production, taking advantage of synergies between its components and integrating production with the conservation of resources (Law 6942—Santiago del Estero).

Following Law 26,331 and to conserve forests in yellow areas (Land-use Planning), FMIL is being promoted in several provinces of the Chaco Region. Within the term FMIL, the planning of all types of livestock activity within a native forest is understood, extending the concept of traditional silvopastoral practices ("pampeanized" ecosystems). Enabling SSP through RBI, in secondary forests, (Kunst et al. 2014; Silberman et al. 2015), is an alternative contemplated within of FMIL. The main difference for traditional SSPs is that it leaves higher tree density and facilitates their regeneration (Kunst et al. 2015). This new approach (FMIL) is based on an integral vision of the environment, balancing the productive capacity of the system, with its integrity and its services, respecting the principle of maintaining and improving the well-being of the farmer and the associated communities. In this way, we seek to increase food production without this implying higher pressure on marginal lands and protected habitats (FAO 2016; Peri et al. 2016a, b, c).

The guidelines for FMIL would contribute to resolving the conflict between agricultural expansion and forest conservation. However, the effort and commitment of the different actors are required. A balanced combination of scientific methods, land change, and ecological policy can increase the equality of decision-making and the sustainability of socio-environmental governance at agricultural borders (Salas Barboza et al. 2019). Additionally, more information on social perspectives can help understand socio-environmental problems, and make inclusive political decisions that are more in line with sustainability in land use (Huaranca et al. 2019).

14.10 Conclusions

In the Chaco, the so-called low-intensity roller-chopping (RBI) is applied to generate SSPs, based on a selective mechanical disturbance of shrub vegetation, which conserves biodiversity and soil characteristics, promoting the natural regeneration of trees and increasing the productivity of the area. Currently, SSPs are designed in degraded secondary forests ("Fachinales"). Manual or mechanical selective clearing, generally used by small and medium producers, eliminates the shrub component, diseased and dead trees, leaving all or part of the tree component to provide a protective cover to the soil, pastures, and animals. According to our experience, it is necessary to apply this disturbance every five years or so; based on scientific information obtained for more than 20 years, we can express that the SSPs are favorable for the Chaco region since they allow increasing meat production while maintaining the base resources, including the soil. In Argentina, the guidelines for "Forest Management Incorporating Livestock" would contribute to resolving the conflict between agricultural expansion and forest conservation. However, the effort and commitment of the different actors are required.

14.11 Future Perspectives

The results presented in this chapter demonstrate the low impact that silvopastoral systems have on soils in the Chaco region, covering aspects related to organic matter and microbial diversity of the soil. These results represent an important antecedent for the construction of threshold levels required for the evaluation of the environmental impact of different agricultural management practices; ignorance of these thresholds is the greatest limitation in the search for more environmentally friendly alternative development practices; These practices must be oriented to value production and a fair redistribution of income, which make it possible to take root and develop opportunities for families who live directly from the land.

All this is happening in the context of a crisis of the traditional model of agro-industrial production, evidenced in the growing environmental deterioration, the excessive consumption of non-renewable energy, the form of appropriation and redistribution of benefits, the misuse of practices of land clearing for silvopastoral use, and the inability to generate sources of jobs; all this leads to a growing depopulation of the countryside (agriculture without farmers); for this reason, interdisciplinary work and the promotion of projects that allow the articulation of an information network to understand the system as a whole, and the construction of intervention protocols are essential, linking the private sector with the institutions that investigate and control the silvopastoral systems.

References

Abdalla M, Hastings A, Chadwick DR, Jones DL, Evans CD, Jones MB, Rees RM, Smith P (2018) Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agric Ecosyst Environ 253:62–81

Abril A (2015) Balance de carbono en los sistemas productivos de regiones áridas. En Pereira S & Galantini JA (Eds.). Impacto de los sistemas actuales de cultivo sobre las propiedades químicas del suelo: Efectos sobre los balances de carbono. INTA. Buenos Aires

Abril A, Bucher EH (1999) The effects of overgrazing on soil microbial community and fertility in the Chaco dry savannas of Argentina. Appl Soil Ecol 12(2):159–167

Abril A, Bucher EH (2001) Overgrazing and soil carbon dynamics in the western Chaco of Argentina. Appl Soil Ecol 16(3):243–249

Abril A, Merlo C, Noé L (2013) Realistic soil C sink estimate in dry forests of western Argentina based on humic substance content. J Arid Environ 91:113–118

Abule E, Smit GN, Snyman HA (2005) The influence of woody plants and livestock grazing on grass species composition, yield and soil nutrients in the Middle Awash Valley of Ethiopia. J Arid Environ 60:343–358

Aguiar S, Mastrangelo ME, Collazo MAG, Sans GHC, Mosso CE, Ciuffoli L, Cáceres D (2018) Cuál es la situación de la Ley de Bosques en la Región Chaqueña a diez años de su sanción? Revisar su pasado para discutir su futuro. Ecol Austral 28(2):400–417

Albanesi A (2008) Rolado y Suelos. In: Kunst C.; R. Ledesma y M. Navall (eds). RBI. Rolado Selectivo de Baja Intensidad. INTA. p 139

Albanesi A (2015) La biodiversidad como insumo de las agrobiotecnologías. Rev Prodiver 2 (1):21–25

Albanesi A, Anriquez A, Polo Sánchez A (2003) Efectos de la agricultura convencional en algunas formas del N en una toposecuencia de la Región Chaqueña, Argentina. Agriscientia 18:3–11

Albanesi AS, Kunst CG, Anriquez AL, Silberman JE, Navall M, Ledesma R, Domínguez-Núñez JA, Duffau RA, Suarez RA, Werenistky D, Raña E, Socolik L, Coria O, Coria D (2013a) Rolado selectivo de baja intensidad (RBI) y sistemas silvopastoriles de la región chaqueña. I. In: Albanesi A, Paz R, Sobrero MT, Helman S, Rodriguez S (eds) Hacia la construcción del desarrollo agropecuario y agroindustrial. De la FAyA al NOA, 1st edn. Magna Publicaciones, Madison, pp 147–174

Albanesi A, Anriquez A, Domínguez-Núñez JA, Silberman J, Kunst C (2013b) Calidad de suelo. Propiedades biológicas y evaluación en ecosistemas semiáridos. In: Albanesi A (ed) Microbiología agrícola. Un aporte de la investigación Argentina, 2nd edn. Ediciones Magna Publicaciones, Tucumán, pp 1–26

An H, Li G (2015) Effects of grazing on carbon and nitrogen in plants and soils in a semiarid desert grassland, China. J Arid Land 7(3):341–349

Anriquez A, Albanesi A, Kunst C, Ledesma R, López C, Rodríguez Torresi A, Godoy J (2005) Rolado de fachinales y calidad de suelos en el Chaco occidental, Argentina. Cienc Suelo 23 (2):145–157

Anriquez AL, Arias S, Silberman JE, Domínguez-Núñez JA, Kunst CR, Albanesi AS (2016) Sistema silvopastoril con diferentes coberturas arbóreas habilitado por rolado de baja intensidad. Impacto de glomalinas y fracciones de carbono del suelo. Cienc Suelo 34(1):33–41

Anriquez A, Barreto G, Silberman J, Domínguez N, Domínguez-Núñez JA (2017) Abundancia y actividad microbiana del suelo en sistemas silvopastoriles de la región chaqueña. Agrotecnia 25:54

Anriquez A, Barrionuevo MC, Silberman JE, Domínguez JN, Domínguez-Núñez JA, Albanesi AS (2018) Impacto de los sistemas silvopastoriles en los microorganismos relacionados al ciclo del N. Cienc Suelo 36:2

Araújo EA, Ker JC, Lima Neves JC, Lani JL (2012) Qualidade do solo: conceitos, indicadores e avaliação. Pesquisa Aplicada Agrotecnol 5(1):187–206

Banegas N, Albanesi AS, Pedraza RO, Dos Santos DA (2015) Non-linear dynamics of litter decomposition under different grazing management regimes. Plant Soil 393(1-2):47–56

Berg WA, Bradford JA, Sims PL (1997) Long-term soil nitrogen and vegetation change on sandhill rangeland. J Range Manag 1997:482–486

Bissett A, Richardson AE, Baker G, Kirkegaard J, Thrall PH (2013) Bacterial community response to tillage and nutrient additions in a long-term wheat cropping experiment. Soil Biol Biochem 58:281–292

Bone J, Barraclough D, Eggleton P, Cabeza M, Jones DT, Voulvoulis N (2014) Prioritising soil quality assessment through the screening of sites: the use of publicly collected data. Land Degrad Dev 25(3):251–266

Bonino EE (2006) Changes in carbon pools associated with a land-use gradient in the Dry Chaco, Argentina. Ecol Gestión Forest 223(1-3):183–189

Bouma J (2010) Implications of the knowledge paradox for soil science. Adv Agron 106:143–171

Bucher EH, Saravia Toledo C (2001) Restauración y manejo sustentable del Gran Chaco. In: Primack R, Roız R, Feinsinger P, Dirzo R, Massardo F (eds) Fundamentos de conservación biológica. Perspectivas latinoamericanas. Fondo de Cultura Económica, Mexico, pp 579–580

Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, Fleskens L, Geissen V, Kuyper TW, Mäder P, Pullerman M, Sukkel W, van Groenigen JW, Brussaard L (2018) Soil quality–a critical review. Soil Biol Biochem 120:105–125

Burbano-Orjuela H (2016) El suelo y su relación con los servicios ecosistémicos y la seguridad alimentaria. Rev Cienc Agríc 33(2):117–124

Caballé G, Fernández ME, Gyenge J, Lantschner V, Rusch V, Letourneau F, Borrelli L (2016) Silvopastoral systems based on natural grassland and ponderosa pine in northwestern Patagonia, Argentina. In: Peri PL, Dube F, Varella A (eds) Silvopastoral systems in Southern South America. Advances in agroforestry. Springer, London, pp 89–115

Caballero J, Palacios F, Arévalos F, Rodas O, Yanosky AA (2014) Cambio de uso de la tierra en el Gran Chaco Americano en el año 2013. Paraquaria Nat 2(1):21–28

Caldas MM, Goodin D, Sherwood S, Campos Krauer JM, Wisely SM (2015) Land-cover change in the Paraguayan Chaco: 2000–2011. J Land Use Sci 10(1):1–18

Camardelli MC, Caruso H, de Bianchi SP, Pérez D, Miranda S (2005) Evaluación de cambios tempranos en la calidad de los suelos relacionados con el carbono en tierras ganaderas del Chaco semiárido salteño. Rev Cient Agropecu 9(2):173–179

Cardoso EJBN, Vasconcellos RLF, Bini D, Miyauchi MYH, Santos CAD, Alves PRL, Paula AM, Nakatani AS, Pereira JM, Nogueira MA (2013) Soil health: looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? Sci Agric 70(4):274–289

Carranza C, Ledesma M (2005) Sistemas silvopastoriles en el Chaco Árido. IDIA Forestales. INTA, Buenos Aires, pp 240–246

Carranza CA, Ledesma M (2009) Bases para el manejo de sistemas silvopastoriles. XIII Congreso Forestal Mundial. Buenos Aires, Argentina. p 9

Carranza ML, Hoyos L, Frate L, Acosta AT, Cabido M (2015) Measuring forest fragmentation using multitemporal forest cover maps: forest loss and spatial pattern analysis in the Gran Chaco, central Argentina. Landsc Urban Plan 143:238–247

Carrera AL, Bertiller MB, Sain CL, Mazzarino MJ (2003) Relationship between plant nitrogen conservation strategies and the dynamics of soil nitrogen in the arid Patagonian Monte, Argentina. Plant Soil 255(2):595–604

Caruso H, Camardelli M, Miranda S (2012) Effect of forest clearing method on indicators of soil quality and the condition of pastures in the semiarid Chaco salteño. Agriscientia 29(2):99–105

Celaya Michel H, Castellanos Villegas AE (2010) Mineralización de nitrógeno en el suelo de zonas áridas y semiáridas. Terra Latinoam 29(3):343–356

Chang MY (1985) Faxinais no Paraná. Instituto Agronômico do Paraná – IAPAR, Londrina

Chará J, Camargo JC, Calle Z, Bueno L, Murgueitio E, Arias L, Dossman M, Hatico RN (2015) Servicios ambientales de sistemas silvopastoriles intensivos: mejoramiento del suelo y restauración ecológica. Sistemas agroforestales: funciones productivas, socioeconómicas y ambientales. CIPAV/CATIE, Cali/Turrialba. pp 331–348

Ciais P, Soussana JF, Vuichard N, Luyssaert S, Don A, Janssens IA, Wattenbach M (2010) The greenhouse gas balance of European grasslands. Biogeosci Discuss 7(4):5997–6050

Collazo MG, Panizza A, Paruelo JM (2013) Ordenamiento Territorial de Bosques Nativos: Resultados de la Zonificación realizada por provincias del Norte argentino. Ecol Austral 23 (2):97–107

Conti G, Díaz S (2013) Plant functional diversity and carbon storage–an empirical test in semi-arid forest ecosystems. J Ecol 101(1):18–28

Conti G, Pérez-Harguindeguy N, Quétier F, Gorné LD, Jaureguiberry P, Bertone GA, Enrico L, Cuchietti A, Díaz S (2014) Large changes in carbon storage under different land-use regimes in subtropical seasonally dry forests of southern South America. Agric Ecosyst Environ 197:68–76

Cui X, Wang Y, Niu H, Wu J, Wang S, Schnug E, Tang Y (2005) Effect of long-term grazing on soil organic carbon content in semiarid steppes in Inner Mongolia. Ecol Res 20(5):519–527

Deng L, Shangguan ZP, Wu GL, Chang XF (2017) Effects of grazing exclusion on carbon sequestration in China's grassland. Earth Sci Rev 173:84–95

Dlamini P, Chivenge P, Chaplot V (2016) Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: a meta-analysis shows. Agric Ecosyst Environ 221:258–269

Dube F, Couto L, Silva ML, Leite HG, Garcia R, Arauco GA (2002) A simulation model for evaluating technical and economic aspects of an industrial eucalyptus-based agroforestry system in Minas Gerais, Brazil. Agrofor Syst 55:73–80

Duval ME, Galantini JA, Iglesias JO, Canelo S, Martinez JM, Wall L (2013) Analysis of organic fractions as indicators of soil quality under natural and cultivated systems. Soil Tillage Res 131:11–19

FAO (2016) El Estado de los bosques del mundo 2016. Los bosques y la agricultura: desafíos y oportunidades en relación con el uso de la tierra. Roma

Fernández PD, Gasparri NI, Jobbágy E, Mazzini F, Oviedo E, Radrizzani A (2018) Stock de carbono en vegetación leñosa aérea y su relación con disturbios en sistemas silvopastoriles del chaco seco argentino. In: Rusch V, Caballé G, Varela S, Diez JP (eds) Actas del IV Congreso Nacional de Sistemas Silvopastoriles, 1st edn. INTA, New York, p 749

Ferreiro-Domínguez N, Rigueiro-Rodríguez A, Rial-Lovera KE, Romero-Franco R, Mosquera-Losada MR (2016) Effect of grazing on carbon sequestration and tree growth that is developed in a silvopastoral system under wild cherry (*Prunus avium* L.). Catena 142:11–20

Galantini JA, Suñer L (2008) Las fracciones orgánicas del suelo: análisis en los suelos de la Argentina. Agriscientia 25:1

Gamarra Lezcano CC, Díaz Lezcano MI, Vera de Ortíz M, Galeano MDP, Cabrera Cardús AJN (2018) Relación carbono-nitrógeno en suelos de sistemas silvopastoriles del Chaco paraguayo. Rev Mex Cienc Forest 9(46):4–26

García Y, Ramírez W, Sánchez S (2012) Indicadores de la calidad de los suelos: una nueva manera de evaluar este recurso. Pastos Forrajes 35(2):125–138

Gil-Sotres F, Trasar-Cepeda C, Leiros MC, Seoane S (2005) Different approaches to evaluating soil quality using biochemical properties. Soil Biol Biochem 37:877–887

Glenk K, McVittie A, Moran D (2012) Deliverable D3. 1: Soil and soil organic carbon within an ecosystem service approach linking biophysical and economic data. SmartSOIL Report

Gómez A, Navall M (2008) Efecto del rolado sobre la estructura del bosque, implicancias para el manejo forestal. In: Kunst C, Ledesma R, Navall M (eds) RBI. Rolado selectivo de baja intensidad. Ediciones INTA, New York, p 137

González C, Abril A, Acosta M (1999) Efecto del fuego sobre la fertilidad edáfica y las comunidades microbianas en el Chaco occidental argentino. Ecol Austral 9(1):3–10

Gonzalez CC, Studdert GA, Kunst C, Albanesi A (2001) Comportamiento de algunas propiedades del suelo en una sabana del Chaco semiárido occidental bajo distintas frecuencias de fuego. Cienc Suelo 19(2):92–100

Greepeace (2017) Newspaper La Nación (Buenos Aires, Argentina, 26 July 2017). https://www.lanacion.com.ar/sociedad/greenpeace-denuncia-desmontes-ilegales-en-el-norte-argentino-nid2047160. Last Accessed 22 November 2019

Hawkes CV, Wren IF, Herman DJ, Firestone MK (2005) Plant invasion alters nitrogen cycling by modifying the soil nitrifying community. Ecol Lett 8(9):976–985

Hoyos LE, Cingolani AM, Zak MR, Vaieretti MV, Gorla DE, Cabido MR (2012) Deforestation and precipitation patterns in the arid Chaco forests of central Argentina. Appl Veg Sci 16:260–271

Huaranca LL, Iribarnegaray MA, Albesa F, Volante JN, Brannstrom C, Seghezzo L (2019) Social perspectives on deforestation, land use change and economic development in an expanding agricultural frontier in Northern Argentina. Ecol Econ 165:106424

Hueck K (1972) Mapa de la vegetación de América del Sur (1:8.000.000). Forstliche Forschungsanstalt Munchen. Gustav Fisher Verlag, Stuttgart

Jangir CK, Panghaal D, Kumar S, Meena RS, Prince A (2017) Enriching soil carbon stock through mitigating soil erosion. In: Rao RK, Sharma PK, Raghuraman M, Singh JK (eds) Agricultural, allied sciences & biotechnology for sustainability of agriculture, nutrition & food security. Mahima Publications, Varanasi, pp 415–419

Jangir CK, Kumar S, Meena RS (2019) Significance of soil organic matter to soil quality and evaluation of sustainability. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 357–381

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE (1997) Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Sci Soc Am J 61 (1):4–10

Kovaleva NO, Kovalev IV (2009) Transformation of lignin in Surface and buried soils of mountainous landscapes. Eurasian Soil Sci 42:1270–1281

Kumar P, Singh RP, Singh AK, Kumar V (2014) Quantification and distribution of agroforestry systems and practices at global level. Hortflora Res Spectr 3(1):1–6

Kumar S, Meena RS, Pandey A, Seema A (2017) Soil acidity management and an economics response of lime and sulfur on sesame in an alley cropping system. Int J Curr Microb Appl Sci 6 (3):2566–2573

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, Cham, pp 337–375

Kunst C, Ledesma R, Basan M, Angella G, Prieto D, Godoy J (2003) Rolado de fachinales e infiltración de agua en el suelo en el Chaco occidental argentino. Rev Invest Agropecuarias 32:105–122

Kunst C, Monti E, Pérez H, Godoy J (2006) Assessment of rangelands of southwestern Santiago del Estero for management and research. J Environ Manag 80:248–265

Kunst C, Ledesma R, Navall M (2008) Rolado Selectivo de Baja Intensidad (RBI) INTA EEA Santiago del Estero. Boletín 57:139

Kunst C, Bravo S, Ledesma R, Navall M, Anriquez A, Coria D, Silberman J, Gómez A, Albanesi A (2014) Ecology and management of the dry forests and savannas of the western Chaco region, Argentina. In: Greer A (ed) Dry forests: ecology, species diversity and sustainable management. Nova Science Publishers, Hauppauge, p 189

Kunst C, Navall M, Coria RD, Ledesma R, Tomsic P, González A, Gómez A, Feuillade D (2015) Guía de Prácticas Recomendables para Sistemas Silvopastoriles en Santiago del Estero: Producir carne y madera conservando el ambiente. EEA Santiago del Estero/INTA

Kunst C, Navall M, Ledesma R, Silberman J, Anriquez A, Coria D, Bravo S, Goméz A, Albanesi A, Grasso D, Domínguez-Núñez J, González A, Tomsic P, Godoy J (2016) Silvopastoral systems in the western Chaco región, Argentina. In: Peri PL, Dube F, Varella A (eds) Silvopastoral Systems in Southern South America, Advances in agroforestry, vol 11. Springer, Cham, pp 63–87

Laino LD, Musálem K, Laino R (2017) Perspectivas para un desarrollo sustentable: un estudio de caso de producción ganadera en la región del Chaco Paraguayo. Población Desarrollo 45:95–106

Lehman RM, Acosta-Martinez V, Buyer JS, Cambardella CA, Collins HP, Ducey TF, Halvorson JJ, Jin VL, Johnson JMF, Kremer RJ, Lundgren JG, Manter DK, Maul JE, Smith JL, Stott DE (2015) Soil biology for resilient, healthy soil. J Soil Water Conserv 70(1):12

Lende SG (2018) Destrucción de bosques nativos y deforestación ilegal: el caso argentino (1998-2016). Papeles Geogr 64:154–180

Li P, Zhang T, Wang X, Yu D (2013) Development of biological soil quality indicator system for subtropical China. Soil Tillage Res 126:112–118

Liu X, Herbert SJ, Hashemi AM, Zhang X, Ding G (2006) Effects of agricultural management on soil organic matter and carbon transformation-a review. Plant Soil Environ 52(12):531

Longo S, Nouhra E, Goto BT, Berbara RL, Urcelay C (2014) Effects of fire on arbuscular mycorrhizal fungi in the Mountain Chaco Forest. Forest Ecol Manage 315:86–94

López-Mársico L, Altesor A, Oyarzabal M, Baldassini P, Paruelo JM (2015) Grazing increases below-ground biomass and net primary production in a temperate grassland. Plant Soil 392 (1-2):155–162

Lorenz K, Lal R (2014) Soil organic carbón sequestration in agroforestry systems. A review. Agron Sustain Dev 34:443–454

Lupatini M, Suleiman AKA, Jacques RJS, Antoniolli ZI, Kuramae EE, de Oliveira Camargo FA, WürdigRoesch LF (2013) Soil-borne bacterial structure and diversity does not reflect community activity in Pampa biome. PLoS ONE 8(10):e76465. https://doi.org/10.1371/journal.pone.0076465

Ma W, Ding K, Li Z (2016) Comparison of soil carbon and nitrogen stocks at grazing-excluded and yak grazed alpine meadow sites in Qinghai–Tibetan Plateau, China. Ecol Eng 87:203–211

Manrique S, Franco J, Núñez V, Seghezzo L, Ciuns CDIDLU (2009) Estimación de densidad de biomasa aérea en ecosistemas naturales de la provincia de salta. Averma 13(6):37–45

Mazzarino MJ, Oliva L, Abril A, Acosta M (1991) Factors affecting nitrogen dynamics in semiarid woodland (Dry Chaco, Argentina). Plant Soil 138(1):85–98

McSherry ME, Ritchie ME (2013) Effects of grazing on grassland soil carbon: a global review. Glob Chang Biol 19(5):1347–1357

Meena RS, Kumar S, Pandey A (2017) Response of sulfur and lime levels on productivity, nutrient content and uptake of sesame under guava (*Psidium guajava* L.) based agri-horti system in an acidic soil of eastern Uttar Pradesh, India. J Crop Weed 13(2):222–227

Meena RS, Mitran T, Kumar S, Yadav GS, Bohra JS, Datta R (2018) Application of remote sensing for sustainable agriculture and forest management. Inform Proc Agric 5:295–297

Meena RS, Lal R, Yadav GS (2020) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Mereles MF, Yanosky AA (2013) Efectos de la fragmentación y la degradación de los hábitats naturales sobre la biodiversidad, en el Paraguay. In: Fernández Reyes L, Volpedo AV (eds) Evaluación de los cambios de estado en ecosistemas degradados de Iberoamérica. Contribución de la Red 411RT0430 "Desarrollo de metodologías, indicadores ambientales y programas para la evaluación ambiental integral y la restauración de ecosistemas degradados" del Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo. Programa CYTED, Buenos Aires, pp 53–72

Morello J (2012) Ecorregión del Chaco Seco. In: Morello J, Matteucci SD, Rodriguez AF, Silva ME (eds) Ecorregiones y complejos ecosistémicos argentinos. Orientación Gráfica Editora, Buenos Aires, p 752

Morello J, Adámoli J (1974) Las grandes unidades de vegetación y ambiente del Chaco argentino. 2da Parte. INTA Serie fitogeográfica N°13

Muñoz-Rojas M, Erickson TE, Dixon KW, Merritt DJ (2016) Soil quality indicators to assess functionality of restored soils in degraded semiarid ecosystems. Restor Ecol 24:S43–S52

Murgueitio E, Calle Z, Uribe F, Calle A, Solorio B (2011) Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. For Ecol Manag 261(10):1654–1663

Navarrete Segueda A, Vela Correa G, López Blanco J, Gamiño R, de Ma L (2011) Naturaleza y utilidad de los indicadores de calidad del suelo. Contactos 80:29–37

Navas Panadero A (2010) Importancia de los sistemas silvopastoriles en la reducción del estrés calórico en sistemas de producción ganadera tropical. Rev Med Vet 19:113–122

Ng E, Patti A, Rose M, Schefe C, Wilkinson K, Smernik R, Cavagnaro T (2014) Does the chemical nature of soil carbon drive the structure and functioning of soil microbial communities? Soil Biol Biochem 70:54–61

Nolte C, Gobbi B, de Waroux YLP, Piquer-Rodríguez M, Butsic V, Lambin EF (2017) Decentralized land use zoning reduces large-scale deforestation in a major agricultural frontier. Ecol Econ 136:30–40

Nyakatawa EZ, Mays DA, Naka K, Bukenya JO (2011) Carbon, nitrogen, and phosphorus dynamics in a loblolly pine-goat silvopasture system in the Southeast USA. Agroforest Syst. https://doi.org/10.1007/s10457-011-9431-2

Patra AK, Abbadie L, Clays-Josserand A, Degrange V, Grayston SJ, Loiseau P, Louault F, Mahmood S, Nazaret S, Philippot L, Poly F, Prosser JI, Richaume A, Le Roux X (2005) Effects of grazing on microbial functional groups involved in soil N dynamics. Ecol Monogr 75 (1):65–80

Paz-Ferreiro J, Fu S (2016) Índices biológicos para la evaluación de la calidad del suelo: perspectivas y limitaciones. Degrad Desarrollo Tierra 27(1):14–25

Peri PL, Monelos HL, Bahamonde HA (2006) Evaluación de la continuidad del estrato arbóreo en bosques nativos de *Nothofagus antartica* (G. Forst) Oerst bajo uso silvopastoril con ganado ovino en Patagonia Sur, Argentina. Actas IV Congreso Latinoamericano de Agroforestería para la Pecuaria Sostenible, Varadero, p 6

Peri PL, Dube F, Varella A (2016a) Opportunities and challenges for silvopastoral systems in the subtropical and temperate zones of South America. In: Peri PL, Dube F, Varella AC (eds) Silvopastoral systems in southern South America. Advances in Agroforestry, vol 11. Springer, Cham, pp 257–270

Peri PL, Dube F, Varella AC (2016b) Silvopastoral systems in the subtropical and temperate zones of South America: an overview. In: Peri PL, Dube F, Varella AC (eds) Silvopastoral systems in Southern South America, Advances in agroforestry, vol 11. Springer, Cham, pp 1–8

Peri PL, Hansen NE, Bahamonde HA, Lencinas MV, von Müller AR, Ormaechea S, Gargaglione V, Soler R, Tejera LE, Lloyd CE, Martínez-Pastur G (2016c) Silvopastoral systems under native forest in Patagonia Argentina. In: Peri P, Dube F, Varella A (eds) Silvopastoral systems in Southern South America. Springer, Suiza, pp 117–168

Peri PL, Banegas N, Gasparri I, Carranza CH, Rossner B, Martínez Pastur G, Cavallero L, López DR, Loto D, Fernández P, Powel P, Ledesma M, Pedraza R, Albanesi A, Bahamonde H, Eclesia RP, Piñeiro G (2017) Carbon sequestration in temperate silvopastoral systems. In: Montagnini F (ed) Integrating landscapes: agroforestry for biodiversity conservation and food sovereignty argentina, Advances in agroforestry, vol 12. Springer, Cham, pp 453–478

Peri PL, Rosas YM, Ladd B, Toledo S, Lasagno RG, Martínez Pastur G (2019) Modeling soil nitrogen content in South Patagonia across a climate gradient, vegetation type, and grazing. Sustainability 11(9):2707

Poeplau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops–a meta-analysis. Agric Ecosyst Environ 200:33–41

Powlson DS, Gregory PJ, Whalley WR, Quinton JN, Hopkins DW, Whitmore AP, Goulding KW (2011) Soil management in relation to sustainable agriculture and ecosystem services. Food Policy 36:S72–S87

Rabot E, Wiesmeier M, Schlüter S, Vogel HJ (2018) Soil structure as an indicator of soil functions: a review. Geoderma 314:122–137

Raiesi F, Riahi M (2014) The influence of grazing exclosure on soil C stocks and dynamics: and ecological indicators in upland arid and semi-arid rangelands. Ecol Indic 41:145–154

Rani K, Sharma P, Kumar S, Wati L, Kumar R, Gurjar DS, Kumar D, Kumar R (2019) Legumes for sustainable soil and crop management. In: Meena RS, Kumar S, Bohra JS, Jat ML (eds) Sustainable management of soil and environment. Springer, Cham, pp 193–215

Rojas JM, Prause J, Sanzano GA, Arce OEA, Sánchez MC (2016) Soil quality indicators selection by mixed models and multivariate techniques in deforested areas for agricultural use in North-West of Chaco, Argentina. Soil Tillage Res 155:250–262

Rosier CL, Moore LD, Wu T, Van Stanjj JT (2015) Forest canopy precipitation partitioning: an important plant trait influencing the spatial structure of the symbiotic soil microbial community. Adv Bot Res 75:215–240

Salas Barboza AGJ, CardónPocoví JM, Venencia C, Huaranca LL, Agüero JL, Iribarnegaray MA, Seghezzo L (2019) Ten years of contested enforcement of the Forest Law in Salta, Argentina. The role of land-change science and political ecology. J Land Use Sci 2019:1–14

Sanchez MC, Lopez JM, Duffau AR, Galizzi FA, Barraza GA, Amarilla ME et al. (2019) Santiago del Estero. In: Casas R, Damiano F (eds) Manual de buenas prácticas de conservación del suelo y del agua en áreas de secano. FECIC. p 560

Sans GHC, Aguiar S, Vallejos M, Paruelo JM (2018) Assessing the effectiveness of a land zoning policy in the Dry Chaco. The Case of Santiago del Estero, Argentina. Land Use Policy 70:313–321

Sarabia L, Solorio FJ, Ramírez L, Ayala A, Aguilar C, Ku J, Boddey RM (2020) Improving the nitrogen cycling in livestock systems through silvopastoral systems. In: Nutrient dynamics for sustainable crop production. Springer, Singapore, pp 189–213

Seghezzo L, Volante JN, Paruelo JM, Somma DJ, Buliubasich EC, Rodríguez HE, Hufty M (2011) Native forests and agriculture in Salta (Argentina) conflicting visions of development. J Environ Dev 20(3):251–277

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019) Growth, yield and quality of cluster bean (*Cyamopsis tetragonoloba*) as influenced by integrated nutrient management under alley cropping system. Indian J Agric Sci 89(11):1876–1880

Silberman J, Anriquez A, Domínguez-Núñez J, Kunst C, Albanesi A (2015) La cobertura arbórea en un sistema silvopastoril del chaco y su contribución diferencial al suelo. Cienc Suelo 33 (1):19–29

Silberman JE, Albanesi A, Grasso D (2016) Manejo de bosques con ganadería integrada: impacto en las comunidades microbianas del suelo. Cienc Suelo 34(2):211–219

Silva GL, Lima HV, Campanha MM, Gilkes RJ, Oliveira TS (2011) Soil physical quality of Luvisols under agroforestry, natural vegetation and conventional crop management systems in the Brazilian semi-arid region. Geoderma 167-168:61–70

Singh AK, Rai A, Singh N (2016) Effect of long-term land use systems on fractions of glomalin and soil organic carbon in the Indo-Gangetic plain. Geoderma 277:41–50

Smith J, Pearce B, Wolfe M (2012) Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? Renew Agric Food Syst 28(1):80–92

Soler RM, Peri PL, Bahamonde HA, Gargaglione V, Ormaechea S, Sánchez-Jardón L, Lencinas MV, Martínez Pastur G (2015) Estado del conocimiento de las investigaciones en sistemas agrosilvopastoriles: una mirada para Sudamérica. In: Peri P (ed). 3° Congreso Nacional de Sistemas Silvopastoriles: VII Congreso Internacional Sistemas Agroforestales. Ediciones INTA. p 716

Stavi I, Bel G, Zaady E (2016) Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems. A review. Agron Sustain Dev 36(2):32

Stone D, Ritz K, Griffiths BG, Orgiazzi A, Creamer RE (2016) Selection of biological indicators appropriate for European soil monitoring. Appl Soil Ecol 97:12–22

Suuster E, Ritz C, Roostalu H, Reintam E, KÖlli R, Astover A (2011) Soil bulk density pedotransfer functions of the humus horizon in arable soils. Geoderma 163(1–2):74–82

Tadesse G, Mohamend Saleem M, Abyie A, Wagnew A (2002) Impact of grazing on plant species richness, plant biomass, plant attribute, and soil physical and hydrological properties of vertisol in east African highlands. Environ Manag 29(2):279–289

Toledo DM, Arzuaga SA, Galantini JA, Vazquez S (2018) Indicadores e índices biológicos de calidad de suelo en sistemas forestales. Cienc Suelo 36(2):1–12

Torres PA, Abril AB, Bucher EH (2005) Microbial succession in litter decomposition in the semi-arid Chaco woodland. Soil Biol Biochem 37:49–54

Vallejo-Quintero VE (2013) Importancia y utilidad de la evaluación de la calidad de suelos mediante el componente microbiano: experiencias en sistemas silvopastoriles. Colombia Forest 16(1):83–99

Vallejos M, Volante JN, Mosciaro MJ, Vale LM, Bustamante ML, Paruelo JM (2015) Transformation dynamics of the natural cover in the Dry Chaco ecoregion: A plot level geo-database from 1976 to 2012. J Arid Environ 123:3–11

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan Region, India. Int J Chem Stud 5(4):1558–1560

Volante JN, Seghezzo L (2018) Can't see the forest for the trees: can declining deforestation trends in the Argentinian Chaco Region be ascribed to efficient law enforcement? Ecol Econ 146:408–413

Wang D, Wu GL, Zhu YJ, Shi ZH (2014) Grazing exclusion effects on above-and below-ground C and N pools of typical grassland on the Loess Plateau (China). Catena 123:113–120

Wienhold BJ, Andrews SS, Karlen DL (2004) Soil quality: a review of the science and experiences in the USA. Environ Geochem Health 26(2):89–95

Wingeyer AB, Amado TJ, Pérez-Bidegain M, Studdert GA, Varela CHP, Garcia FO, Karlen DL (2015) Soil quality impacts of current South American agricultural practices. Sustainability 7 (2):2213–2242

Xiong D, Shi P, Zhang X, Zou CB (2016) Effects of grazing exclusion on carbon sequestration and plant diversity in grasslands of China—a meta-analysis. Ecol Eng 94:647–655

Zak MR, Cabido M, Hodgson JG (2004) Do subtropical seasonal forests in the Gran Chaco, Argentina, have a future? Biol Conserv 120(4):589–598

Zornoza R, Acosta JA, Bastida F, Domínguez SG, Toledo DM, Faz A (2015) Identification of sensitive indicators to assess the interrelationship between soil quality, management practices and human health. Soil 1(1):173–185

15

Water Resource and Use Efficiency Under Changing Climate

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Abstract

Presently, groundwater contributes 60% of total irrigation, and due to overdrafting of groundwater, it has reached the level of water crisis in many states of India. Climate change (CC) also poses many threats, especially in terms of quality, quantity, and sustainable use of water resources, which require judicious use of water management technologies to improve agricultural water productivity. There is need to harvest each drop of water and use efficiently and effectively in CC. Thus, the scope of improving water use efficiency (WUE) and enhancing water productivity in agriculture under the present CC scenario has taken to be the priority area of interest. Therefore, there is a need to improve either the irrigation method or inculcation of multi-sensor-based technology, which makes the irrigation system automated, or interventions of agronomical measures in fields. Considering this, Government of India has also taken initiative by launching PMKSY (*Pradhan Mantri Krishi Sinchayee Yojana*) to fulfil the dream of "More crop per drop" to familiarize modern irrigation methods and "*Har Khet Ko Pani*" by promoting on-farm development, integrated farming as well as integrated approaches in watershed management in farmers' fields. Apart from it, recent advances in sensor technologies and the Internet of things (IoT) have made automated irrigation scheduling, which helps in real-time monitoring of soil moisture. But there is need to conduct more research to develop a low-cost automated irrigation system for wide acceptability by small and marginal farmers that will help fulfil the dream of "More crop per drop." The "More crop per drop" paradigm provides the pathway to solve many problems related to water management by improving overall agricultural water productivity. By considering the facts, this chapter aims to describe the current scenario of CC as well as its uncertainty in irrigation water availability. It also takes a critical look at the present status and issues of irrigation methods. Lastly, this chapter discusses the technological interventions, including both engineering and agronomical measures to address the challenges of irrigation water management and to enhance WUE.

Keywords

Agronomical measures · Water productivity · Climate change · More crop per drop · Water use efficiency

Abbreviations

BCM	Billion cubic meters
CC	Climate change
CGWB	Central Ground Water Board
CO_2	Carbon dioxide
CWC	Central Water Commission
DSR	Direct seeded rice
DSS	Decision support system
FDR	Frequency domain reflectometry
FIRB	Furrow Irrigated Raised Bed
FYM	Farmyard manure
GCM	Global climate model
GDP	Gross domestic production
GHGs	Greenhouse gases
IoT	Internet of things
IPCC	Intergovernmental Panel on Climate Change
ISMR	Indian summer monsoon rainfall
IWR	Irrigation water requirement
$\mathrm{kg\ ha^{-1}\ mm^{-1}}$	Kilogram per hectare per millimeter
$\mathrm{kg\ m^{-3}}$	Kilogram per cubic meter
$\mathrm{kg\ mL^{-1}}$	Kilogram per milliliter
LDPE	Low-density polyethylene
LPA	Long-period average
LVDT	Linear variable differential transducer
M ha	Million hectares
$\mathrm{m^3}$	Cubic meter
mm	Millimeter

OECD	Organization for Economic Co-operation and Development
PCC	Plain cement concrete
PIB	Press information bureau
PMA	Phenyl mercuric acetate
PMKSY	Pradhan Mantri Krishi Sinchayee Yojana
SRI	System of rice intensification
SST	Sea surface temperature
TDR	Time domain reflectometry
WAE	Water application efficiency
WCE	Water conveyance efficiency
WUE	Water use efficiency

15.1 Introduction

India is an agrarian country which consists of 17.4% of the global population and 4% of freshwater resources, of which 80% is being used in agriculture (Anonymous 2013). Therefore, agriculture is the largest consumer of freshwater resources. But, due to the burgeoning population and increasing demands from other sectors, its share is projected to be reduced to 69% by 2025 (Goyal et al. 2016). As per the environmental outlook report 2050 of Organization for Economic Co-operation and Development (OECD 2014), India is expected to experience acute water crisis by 2050. Water is a vital resource for life on earth. India is not a water-rich nation and that is why optimal and sustainable strategic planning of this limited resource has now become an arduous task. The country obtains an annual volume of 4000 BCM (Billion Cubic Meters) water via rainfall each year, but about half of this (48%) is being utilized in surface and groundwater systems. Only 18–20% of this water is used due to lack of effective infrastructure, inadequate water management, and insufficient storing capacity, rest goes waste (Dhawan 2017). The average annual precipitation in India accounts to approximately 1174 mm (millimeter), out of which 3/4th is received in short periods of 4 months resulting in excess runoffs during the Indian Summer Monsoon Rainfall (ISMR) season (MOES IMD 2019). Constant demands for water are created by rising population, increased urban sprawl, and accelerated industrialization coupled with increased agricultural production. In India, more than 70% of food grains are produced from irrigated agriculture, where surface and groundwater play a crucial role (Gandhi and Namboodiri 2009).

Agriculture is the largest consumer of water at the moment and may proceed to do so in the upcoming years in the country, requirements of other sectors of the economy like household and industries have also increased significantly. It is also predicted that per capita annual average water availability will decline to 1340.94 and 1139.82 m^3 (cubic meter) by 2025 and 2050, respectively (CWC 2015). Presently, groundwater resource has also reached the level of water crisis in many states of India like Punjab, Haryana, Rajasthan, Delhi, etc. (CWC 2015). The population of India is expected to reach 1640 million in 2050 (Gupta and Deshpande 2004), which will lead to greater demand for irrigation water in agriculture to meet the requirements of food grains for the rising population. It will require an extension of infrastructure facilities and better use of resources. Natural water resources are being renewed and restored via the incessant evaporation, rainfall, and runoff cycles. The water cycle is regulated by environmental and geological factors which cause fluctuations in rainfall and evaporation, which in response determines the flow of runoff and availability of water over time. Findings in recent decades and climate change (CC) projections suggest an increased incidence of the complexities in the water cycle in terms of both space and time (IPCC 2013). Consequently, gaps in demand and supply of water are widening. At global as well as local scale, fluctuations in the availability of water are primarily increasing due to environmental conditions, CC, and changes in anthropogenic activities. The population explosion, combined with massive economic programs, has introduced new hurdles in the management of water resources. CC also poses many threats to quality, quantity along with sustainable use of water resources which necessitate the judicious usage of available water reserves (Gautam and Singh 2015; Meena et al. 2018a, b). Therefore, there is a terrible need to improve water use efficiency (WUE) in Indian agriculture so that more agricultural output is obtained from per drop of water used, i.e. "More crop per drop" can be achieved. The approach of "More crop per drop" is need of the hour to save our precious resource, i.e. water for meeting its increasing demand in domestic and industrial purposes effectuated by the burgeoning Indian population (Kumar and van Dam 2009). Government of India has also emphasized on enhancing WUE, on-farm water productivity, and water conservation to use every drop of water more efficiently at field level. Presently, the widely used irrigation method in India is surface irrigation which is having very squat irrigation application efficiency. To tackle these problems, micro-irrigation system (drip and sprinklers) plays an important role. It also helps the farmers to maximize farm profit with enhancing input use efficiency. But, the most important issue from the farmer's perspective is irrigation scheduling, i.e. farmers are unable to decide when to irrigate and how much to irrigate a particular crop through different irrigation methods. It gives more emphasis on the use of different soil moisture sensors and canopy sensors for irrigation scheduling. However, in the last decade, new advanced technology has been developed and also implemented with data transmission systems on near real-time, so that farmers can easily control their fields using mobile from remote areas, but higher skills are required for its wider acceptability (Kumar et al. 2016a). Agronomical interventions also help in water-saving and moisture conservation and significantly contribute in achieving the goal of "More crop per drop." In this context, this chapter is formulated to overview the current water availability in the context of Indian agriculture, the impact of CC on water resources, the strategies to enhance WUE (both engineering and agronomical aspects), and recent advances in irrigation water management as well as policy instrumentation.

15.2 Overview of Available Water Resources in India

Of the world's total resources of water, only 2.5% is freshwater, and the remaining 97.5% is oceanic, non-usable (Gleick et al. 1993; Shatat et al. 2013; USGS 2019) (Fig. 15.1). About 70% of this freshwater is locked in frozen form, and 30% is groundwater, whereas only a minute fraction of it is accessible as surface water (Gleick et al. 1993; Shatat et al. 2013; USGS 2019) (Fig. 15.2). Of these available freshwater resources, around 70% is used for irrigation in agriculture, whereas

Fig. 15.1 Global water resources

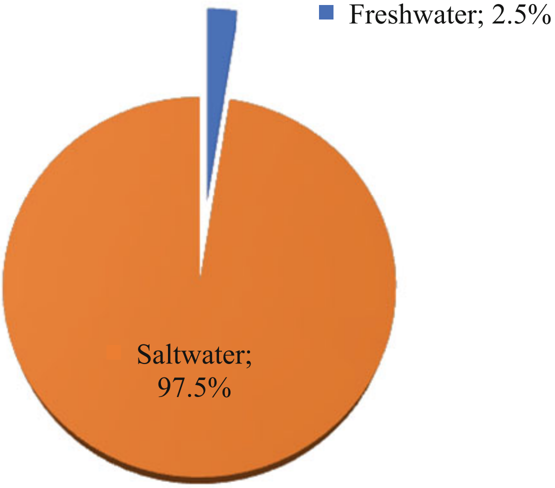
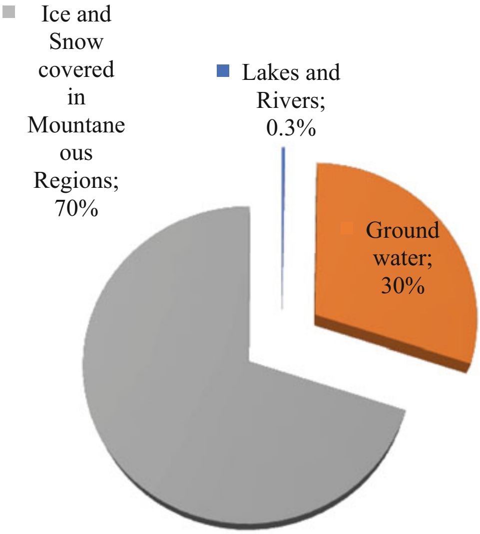


Fig. 15.2 Global freshwater resources



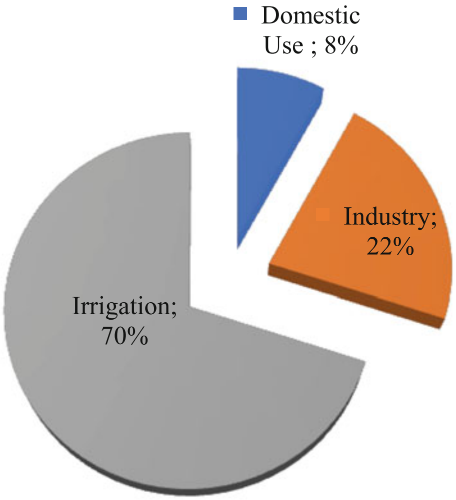


Fig. 15.3 Global freshwater use

22 and 8% of this is being used for industrial and domestic purposes (UNESCO 2003; IAEA 2011; Shatat et al. 2013; FAO 2017) (Fig. 15.3).

In India, as per the CWC (2016–17), total annual precipitation (all forms, viz. drizzle, rain, sleet, snow, ice pellets, graupel, and hail) is calculated to be around 4000 BCM that is the principal source of water, out of which around 3000 BCM downpours during ISMR season. The country's total surface water supply is approximately 1986.5 BCM. It has been estimated that only around 690 BCM of water is used for various purposes because of extremely high uncertainty in rainfall, which hinders the safe storage of all flash and peak flows and the unavailability of appropriate storage facilities in the hills and plains. It is also projected that around 433 BCM of groundwater is available which can be utilized for irrigation and agricultural purposes. Therefore, an annual sum of 1123 BCM of accessible surface and groundwater is available for irrigation.

There is an approximate 252.8 M ha (million hectares) gross catchment area of Indian rivers (CWC 1993, 2019b; Dehadrai 2003; OGD 2018). The Ministry of Water Resources has divided the entire nation into 20 different river basins, consisting of the major, medium, and small river systems. Catchment area, the average annual potential of the river and estimated utilizable flow (excluding groundwater) of the major river basins in India are depicted in Figs. 15.4, 15.5, and 15.6, respectively.

The inland-water resources available in India can be categorized as rivers, canals, reservoirs, ponds, dams, beels, oxbows, lakes, etc. covering an area of around 7 M ha (other than rivers and canals), out of which the reservoir is one of the primary entities for storage of water (Petr 2003; Dehadrai 2003; Jain et al. 2007). The Central Water Commission (CWC) tracks weekly live storage status of the 120 reservoirs of India (CWC 2020). According to CWC (2020), the cumulative live storage capacity of all these reservoirs is approximately 170.3 BCM, which is around 66% of the projected

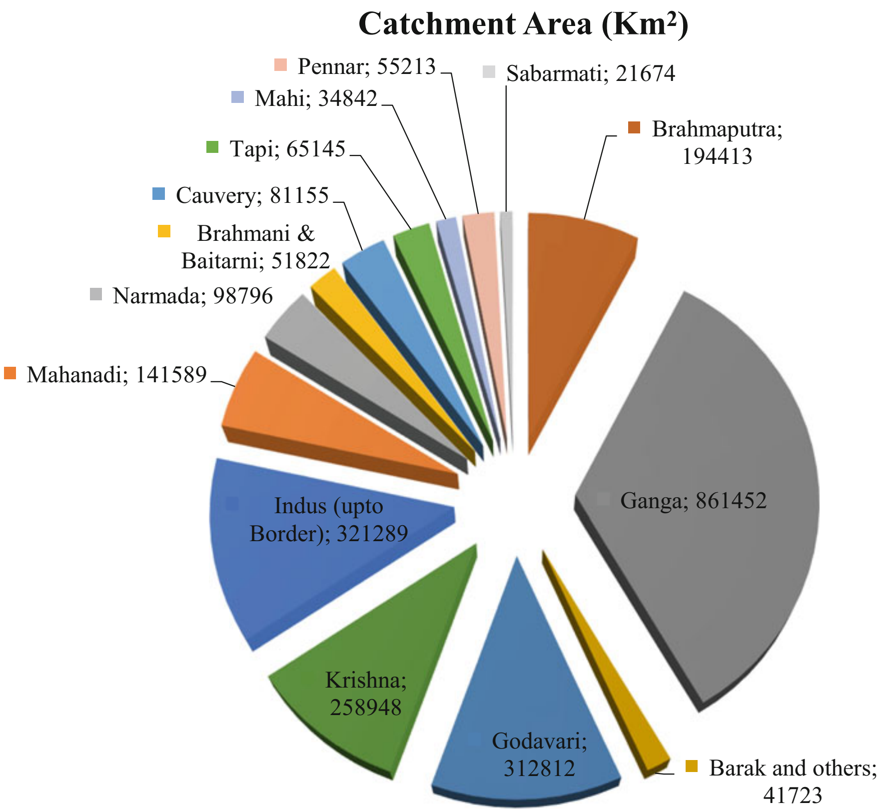


Fig. 15.4 The catchment area of major river basins in India (Data source: CWC 1993, 2019b; Dehadrai 2003; OGD 2018)

potential storage capacity of 257.8 BCM of India. As per the CWC report, live storage available in these reservoirs by second fortnight of January 2020 is 126.6 BCM, corresponding to 81.9 BCM for the same period of the year 2019, and average live storage of 87.9 BCM for the same period of previous 10 years. Therefore, the live storage available in all the reservoirs monitored by CWC by January 2020 is 155% as compared to the live storage of previous year and 144% as compared to the last 10 years'-average for the corresponding period.

The Northern region comprises Himachal Pradesh, Punjab, and Rajasthan with eight reservoirs under CWC surveillance having a total live storage capacity of 19.17 BCM (CWC 2020). The Eastern part of India (Jharkhand, Odisha, West Bengal, Tripura, and Nagaland) with 17 reservoirs is having a total live storage capacity of 19.37 BCM. The Western region (Gujarat and Maharashtra) with 41 reservoirs under CWC watch has overall live storage capacity of 34.84 BCM. The Central part (Uttar Pradesh, Uttarakhand, Madhya Pradesh, and Chhattisgarh) is having 18 reservoirs under CWC supervision that have a combined live storage capacity of 44.14 BCM.

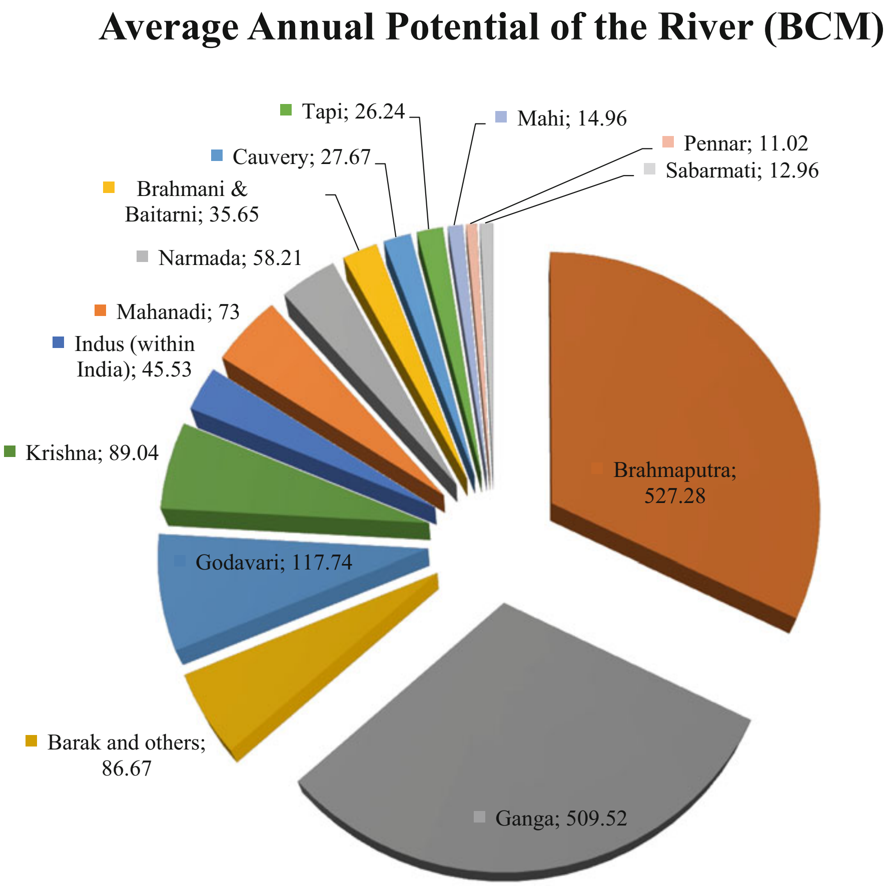


Fig. 15.5 The average annual potential of the major rivers in India (Data source: CWC 2019a)

The Southern region encompassing Andhra Pradesh (AP), Telangana (TG), AP and TG (two combined projects in both states), Karnataka, Kerala, and Tamil Nadu has 36 reservoirs under CWC monitoring with a cumulative live storage capacity of 52.81 BCM. The region-wise number of reservoirs, current year storage along with maximum storage capacity of reservoirs, and deviation of current year storage from the last 10 years mean storage of reservoirs are depicted in Figs. 15.7, 15.8, and 15.9, respectively. It is clear from Fig. 15.9 that the West Bengal followed by Tamil Nadu had a maximum deviation of current year storage in the reservoir from the last 10 years mean storage, which depicts the depletion of the available water resources in these states. The states of Punjab, Rajasthan, Andhra Pradesh, Telangana, Madhya Pradesh, Gujarat, and Karnataka are also showing the same reduction. It clearly indicates that the availability of water from these reservoirs is drastically decreasing with times, which accentuates the immediate need of conserving these water resources and judicious use of water obtained from them.

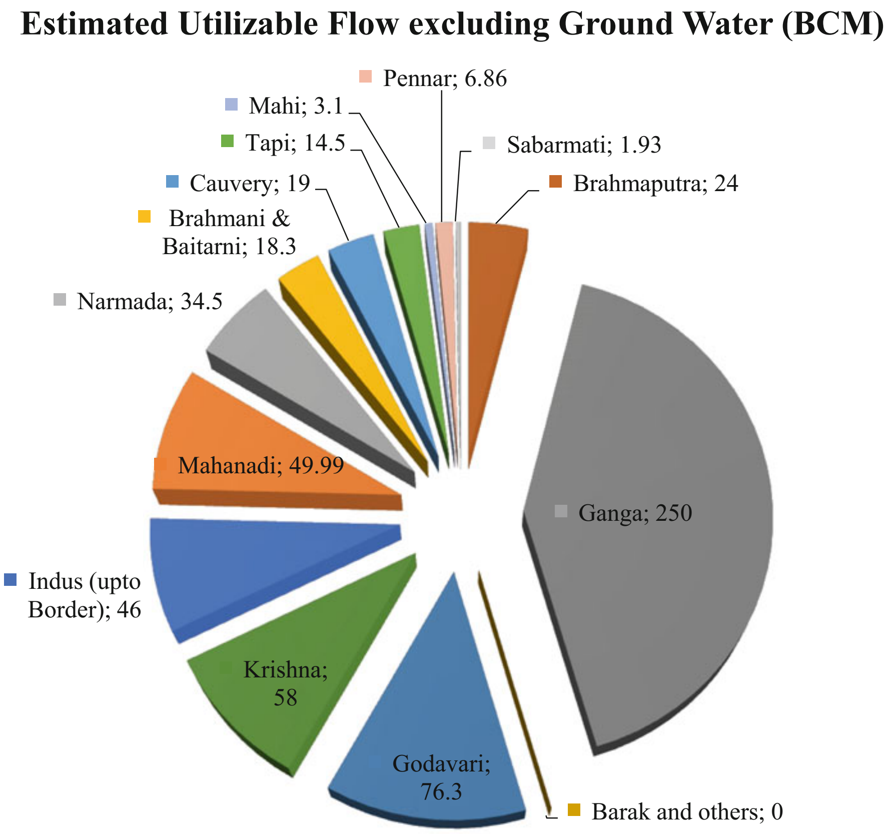


Fig. 15.6 Estimated Utilizable Flow (excluding groundwater) of the major river basins in India (Data source: CWC 1988, 2019b)

The gross potential for consumable or utilizable groundwater per annum in India is deemed to be 433 BCM (CGWB 2017). After making allowances for drinking and industrial water supply and other uses (other than irrigation), the annual capacity for irrigation is 361 BCM (Datta 2019), which is about 83% of total potential. The irrigation water potential from groundwater has steadily increased, from 6.5 M ha in 1951 (Dehadrai 2003) to 96.4 M ha in 2015 (DES, MOA, FW 2014–15). Groundwater contribution to the country's total food grain and agricultural production is considerable because more than 50% of the irrigated regions utilize groundwater and the contribution is more than 80% in various districts. The annual extraction of groundwater has grown from 10–20 BMC to 300 BMC in previous six decades since 1950 (Shah 2009). Groundwater is a resource which is replenished and recharged every year, yet its spatial and temporal availability is inconsistent which keeps on fluctuating, while the major contributor to groundwater recharge is precipitation, the amount of which is variable itself. Thus, a practical quantitative assessment, based

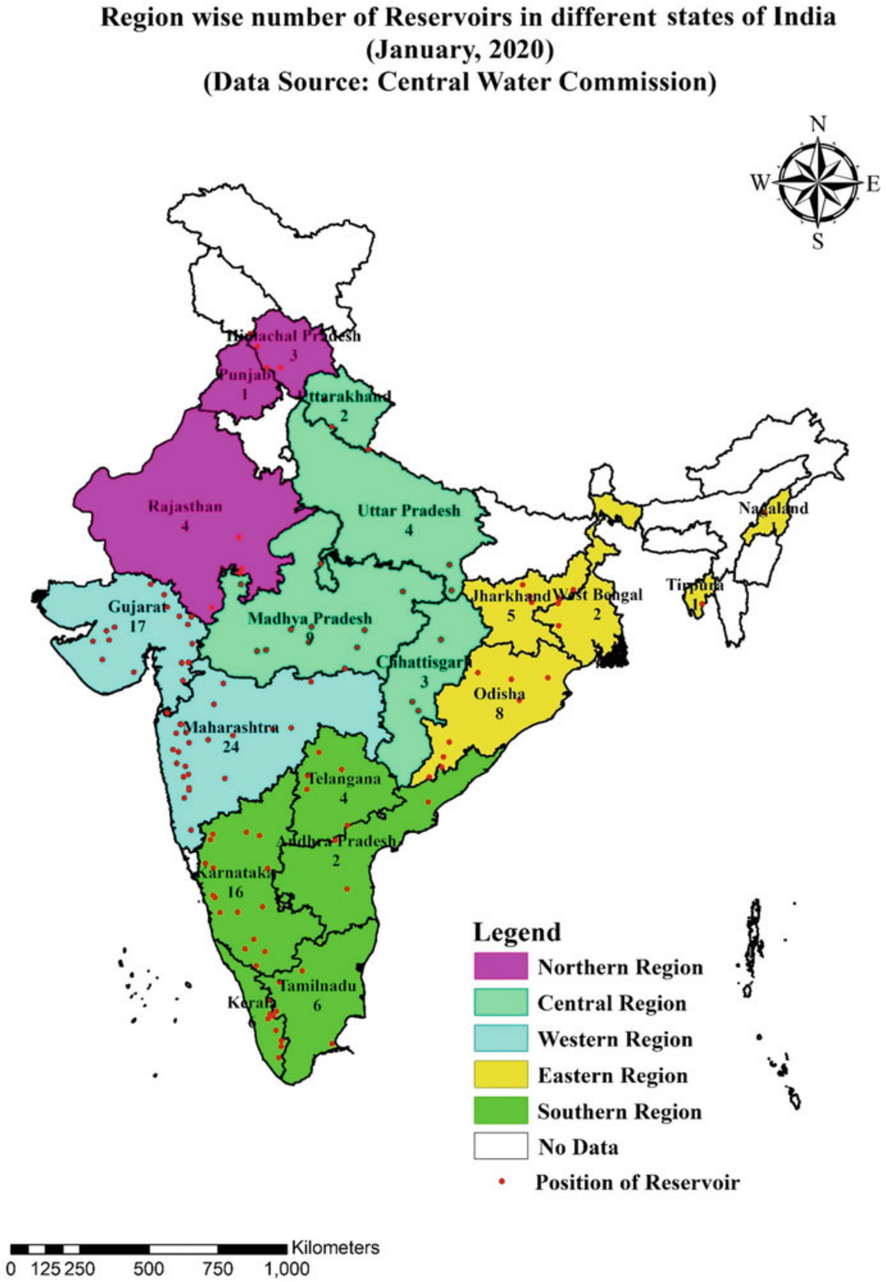


Fig. 15.7 Map depicting the region-wise number of reservoirs in different states of India

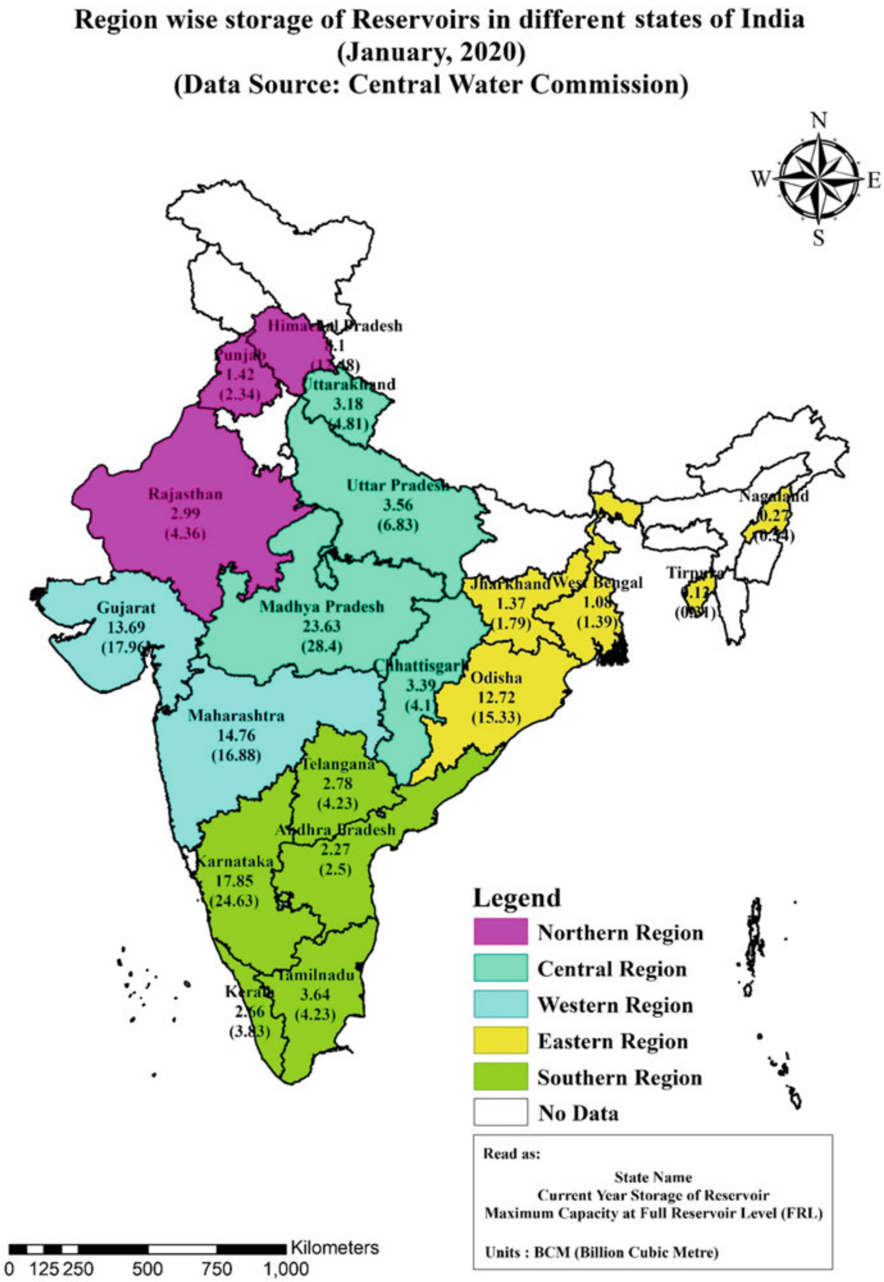


Fig. 15.8 Map depicting region-wise current year storage and maximum storage capacity (at Full Reservoir Level) of reservoirs in different states of India

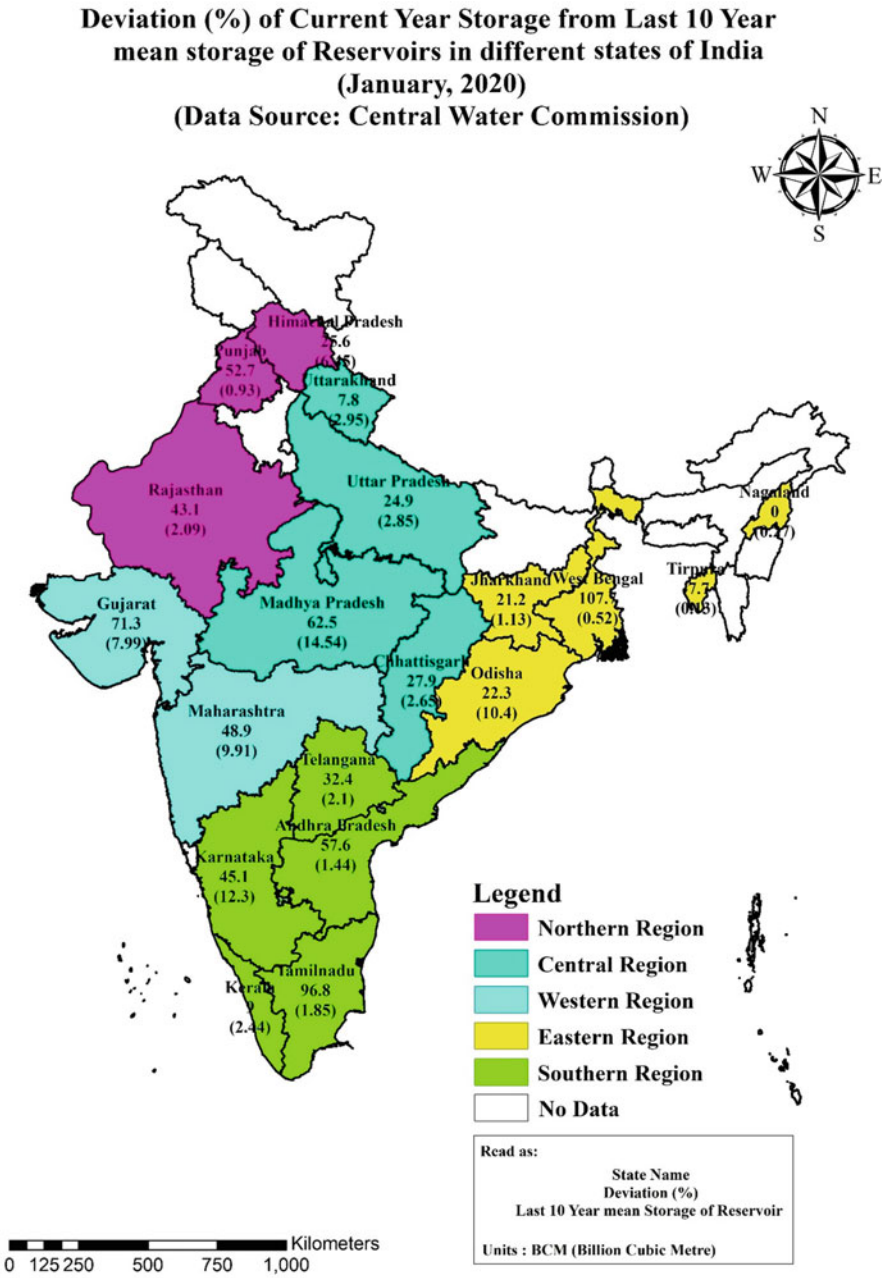


Fig. 15.9 Map depicting region-wise deviation (in percentage) of current year storage from the last 10 years mean storage of reservoirs in different states of India

on reasonably valid scientific principles, is vital for sustainable use of groundwater resources. The evaluation of the mining groundwater is performed by taking into account the data from Minor Irrigation Census and sample surveys by the State Departments of Groundwater. In 2017, the entire nation had an extracted total annual groundwater of around 248.7 BCM (CGWB 2017). Other than precipitation, the underground aquifers got supplemental recharge by sources like inlets and seepage of water from canals and field channels, in-situ ponds and tanks in agricultural fields, river drainage, and deep percolation losses from irrigated agricultural and horticultural areas. The significant portion of water supplied to cultivated crops percolates beyond the root zone in most canal-covered parts of the nation, which adds and recharges the groundwater. Depending upon the overall length of major canals and distributaries, India's total possible annual recharge is projected to be 5.5 M ha-meters because of seepage losses. As per international standards, a nation is listed as water-stressed if the water availability per capita is below 1700 m^3 and as water scarce if it is further below 1000 m^3. The per capita average annual water availability in the country was estimated to be 1816 m^3 and 1545 m^3 in 2001 and 2011, respectively, which could further decrease to 1486 m^3 in 2021 (PIB 2019b). So, India is a water-stressed nation which is moving toward becoming water scarce. Therefore, there is a dire need to take action for checking the depletion in the quantity and quality of our surface and groundwater resources by enhancing the WUE of the system.

15.3 Status of Water Use in Indian Agriculture

Being the chief producer of fresh fruits, vegetables, milk, major spices, various crops like jute (*Corchorus* sp.), staples, millets, and castor (*Ricinus communis*) oil seed, and the second largest producer of overall farm inputs, wheat (*Triticum aestivum*) and rice (*Oryza sativa*), agriculture is the backbone of the Indian economy. Agriculture share in GDP (Gross Domestic Production) has fallen to 17.1% in 2017–18, as compared to 17.9% in previous year (PIB 2018). Since more than half of the Indian population depends on agriculture, its proportion in employment and livelihood remains relatively substantial. In 2018, agriculture and the associated industries, such as forestry and fisheries, accounted for 14.39% of GDP and employed about 42% of the workforce (MOSPI 2019).

Out of the overall geographical area of 328.7 M ha, the total cultivable land of India is around 181.86 M ha. In our country, with overall cropping intensity of 141.6%, the gross cropped area is 198.3 M ha and the net sown area is 140.1 M ha (MOSPI 2018–19). Out of this, 96.4 M ha is gross irrigated and 68.3 M ha area is net irrigated. Out of the net irrigated area, 31.6 M ha land is irrigated through tube-wells, 16.2 M ha through canals, 11.4 M ha through other wells, 1.72 M ha through tanks, and rest 7.5 M ha through other sources (DES, MOA, FW 2014–15). Most of the irrigated area is covered by wheat and rice crop (Fig. 15.10).

The gross as well as the net irrigated area along with the percentage of total cultivated area under irrigation in different states of India is depicted in Fig. 15.11. If

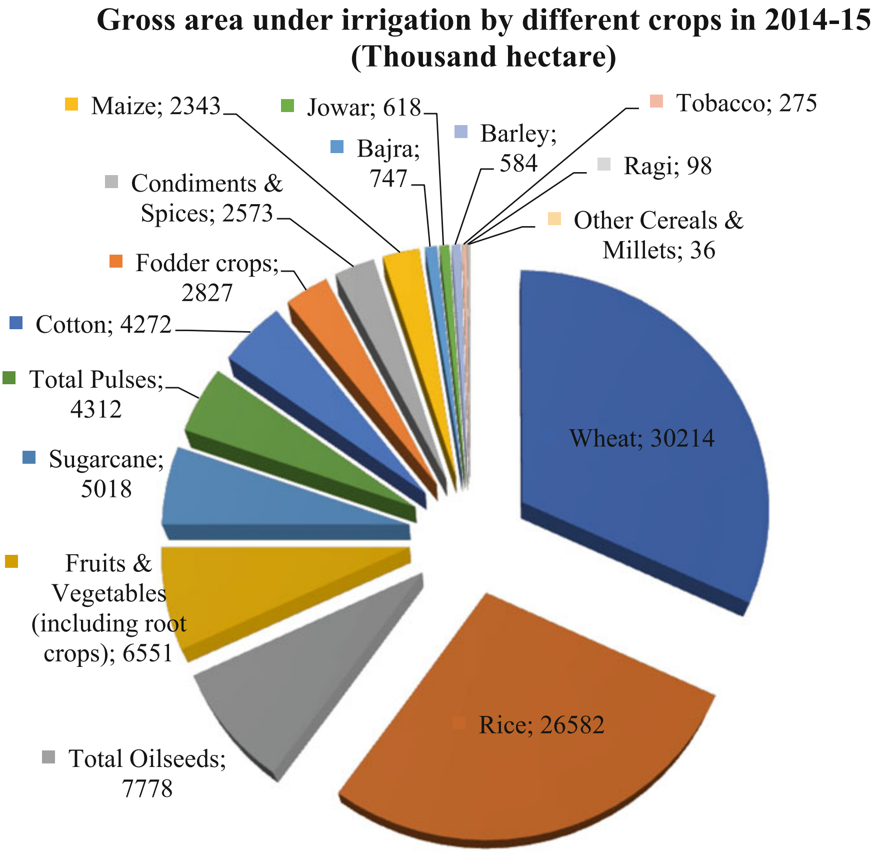


Fig. 15.10 Crop-wise gross area under irrigation in India (in 2014–15)

we see the state-wise area under irrigation in India, then it is clear that only a few states like Punjab, Haryana, and Uttar Pradesh have gross irrigated area of more than 70% whereas in most of the states, it is <50% indicating that most of the agricultural land in India is rain fed. India has approximately 67% of the net sown area under rain-fed agriculture that contributes to 44% of the total food grain production. India has an ultimate irrigation potential of 140 M ha. But a significantly large area under cultivation in India is still dependent on the ISMR. So, for stable agricultural production to ensure food security of the Indian population, constant development in the nation's irrigation potential is required. There is a dire need to expand the irrigated area in India by converting the rain fed area into irrigated so that the boost in crop productivity for meeting the nutritional demand of the increasing population can be realized.

The irrigation system for agricultural activities consists of an irrigation network of streams and canals from the river, groundwater, reservoirs, wells, tanks, and other resources like ponds and tanks used to harvest rainwater. Groundwater source has

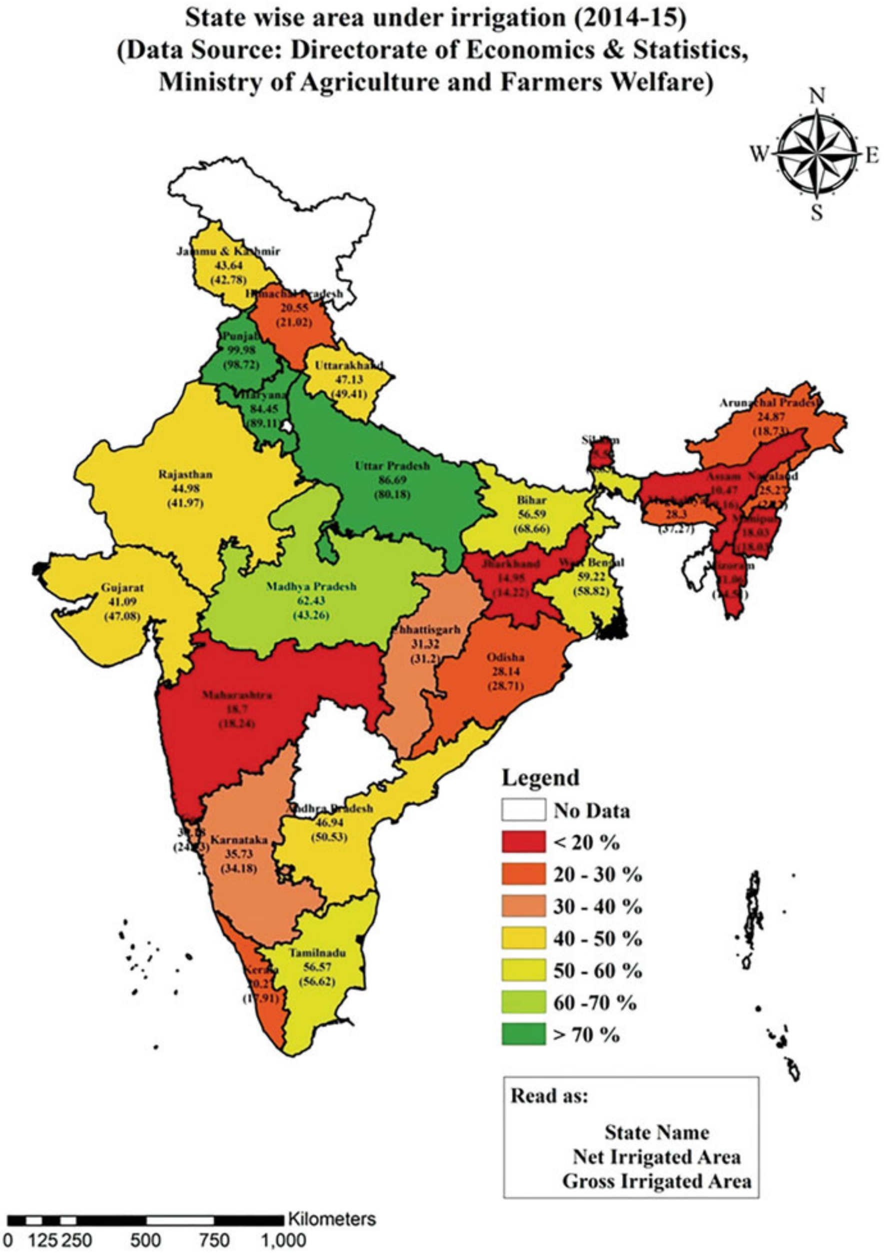


Fig. 15.11 Map depicting gross irrigated area, net irrigated area, and percentage of the cultivated area under irrigation in different states of India

constantly been the stability of drinking water and the foundation of Indian agriculture. Around 62% of groundwater is used for irrigation (DWR, RD, GR 2020). Agriculture is the primary user of groundwater assets. Around 89% of the total share of annual extracted groundwater, i.e. 221.5 BCM, was used for irrigation and a mere fraction of 27.2 BCM, which is around 11% of total extraction was utilized for domestic and industrial purpose. The percentage of extracted groundwater utilized for irrigation by different states in 2017 is shown in Fig. 15.12. The states like Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, Gujarat, Maharashtra, West Bengal, etc. are highly dependent on groundwater for irrigation (Fig. 15.12). This over-dependence on groundwater beyond sustainable limit has resulted in the noteworthy decrease in groundwater level in many states, especially in Northwest India. As per the Central Ground Water Board (CGWB 2017), 39% of wells are depicting the decline in groundwater level. Fifteen states have been classified as "over-exploited" in withdrawal of groundwater. NASA GRACE Satellite data reveal that aquifers in northwest India are in extreme water stress. This indicates that our country may become deprived of groundwater shortly if the status quo continues.

The application and use efficiencies of irrigation water in India are low due to irrational, non-judicious, and improper utilization of irrigation water. Most of the irrigation projects have low operational efficiency of 30–40% as 60–70% of irrigation water get lost during conveyance and application time. There is a great scope in reducing the conveyance losses of 60–70% in Indian irrigation system by the appropriate lining of the whole irrigation project, which can significantly enhance the WUE of the whole irrigation system.

The present status of WUE of various irrigation methods is given in Table 15.1. The traditional irrigation method in India is surface irrigation in the form of either uncontrolled flooding or controlled flooding like check basins, borders, and furrows having very low (35–40%) irrigation application efficiency due to more evaporation and deep percolation losses in fields. Presently, most of the area in India is irrigated by traditional methods. Still there is a scope of improving WUE of surface water and groundwater for irrigation purpose by 30% and 20%, respectively CWC (2014). To improve the conveyance, distribution, and application efficiency, micro-irrigation system (Drip and Sprinklers) came into the picture. Farmers can achieve high irrigation efficiency up to 80–90% by the manually controlled micro-irrigation system. The area under micro-irrigation systems having higher WUE is only 11.41 M ha which is very miserable as compared to their potentials of 71.23 M ha (Priyan and Panchsal 2017). The state-wise area under sprinkler and drip irrigation in India is given in Figs. 15.13 and 15.14. So, there is a lot of scope in improving WUE in Indian agriculture by adopting efficient practices.

15.4 Concept of Water Use Efficiency

In general, efficiency of a system is the percentage of output derived from the applied inputs (Hillel 1997). So, WUE denotes the relative output obtained from the water use. Water use efficiency (WUE) can be defined in many ways as it's a broad

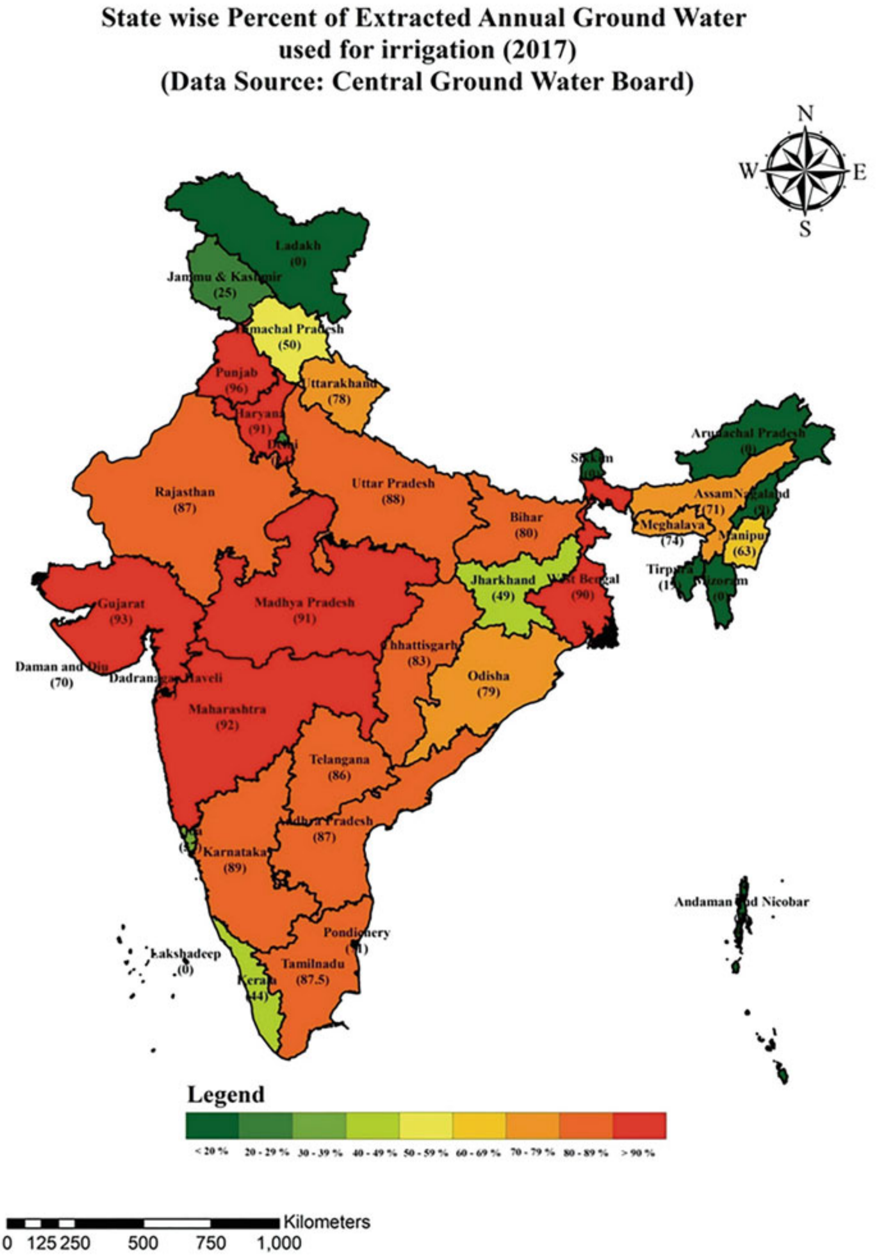


Fig. 15.12 Percentage of extracted annual groundwater used for irrigation in different states of India

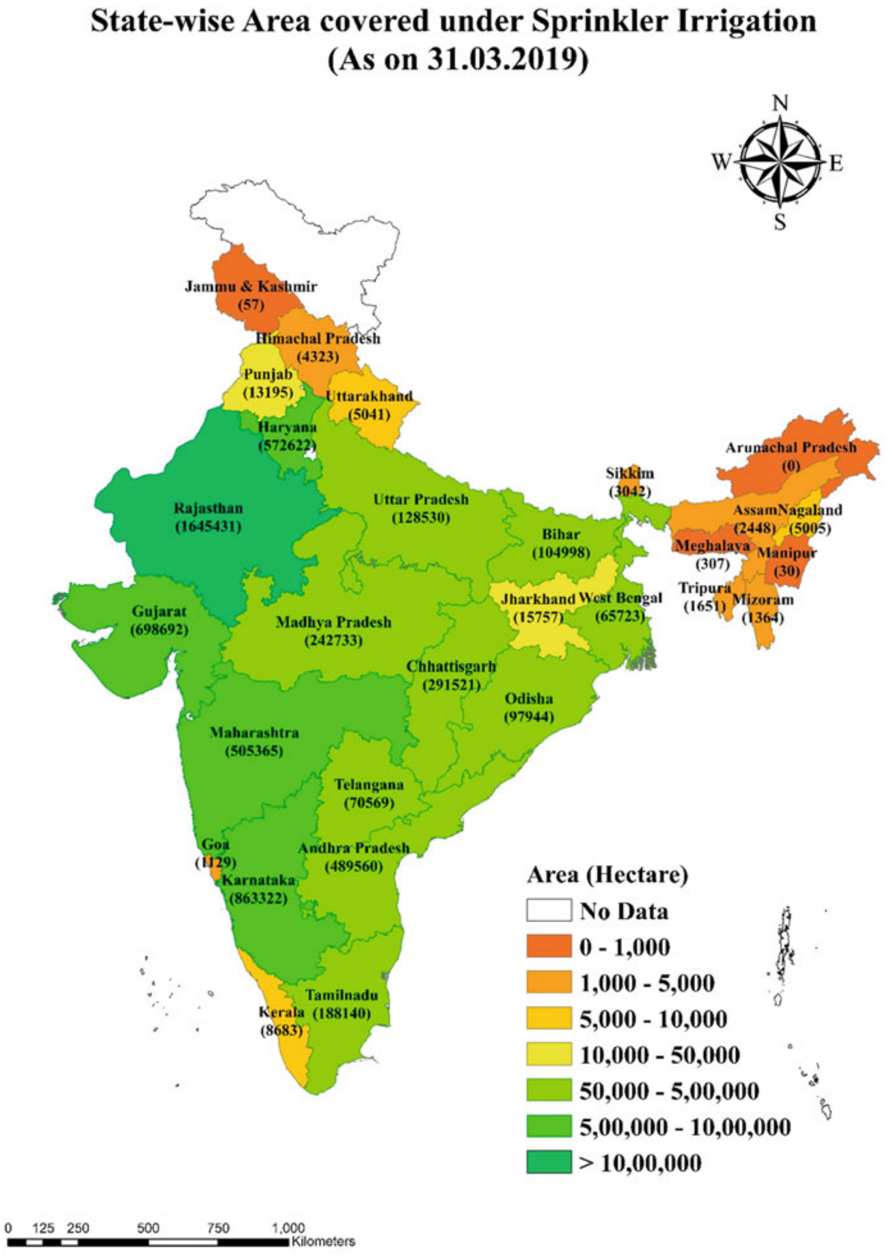
Table 15.1 Water Use Efficiency of various methods for irrigation

Method	Water use efficiency (%)
Conveyance through unlined canal for surface water	55–60
Conveyance through lined canal for surface water	70–75
Flood irrigation	65
Furrow irrigation	80
Sprinkler irrigation	85
Drip irrigation	90
Overall efficiency for surface water system	30–65
Overall efficiency for groundwater system	65–75

(Source*:* CWC 2014)

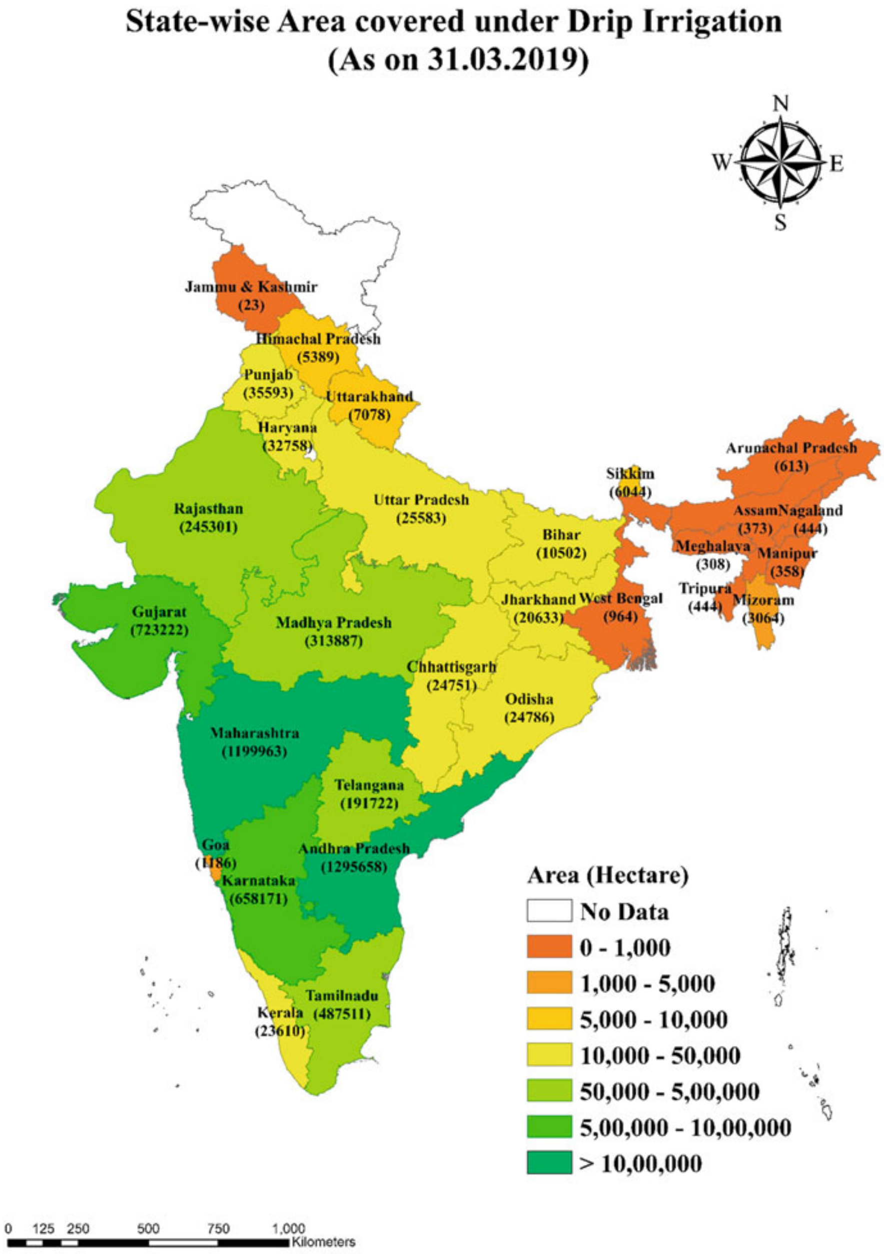
concept. In general, it is the ratio of grain yield and amount of water required to produce same yield. In other way, it can be said that it is the harvested yield of crop achieved from the applied or naturally available amount of water through irrigation, rainfall, and contribution from soil water content (Ali and Talukder 2008). The term "water use efficiency" varies from the crop, farm to the irrigation project level. Therefore, this term doesn't have any unique definition. Barrett Purcell and Associates (Purcell 1999) pointed out that the term "efficiency" is in fact a dimensionless term that denotes the ratio of figures having the same unit. But the term "WUE" has units of kg m^{-3} (kilogram per cubic meter) or kg ha^{-1} mm^{-1} (kilogram per hectare per millimeter) or kg mL^{-1} (kilogram per milliliter) if expressed in terms of crop yield with respect to water consumed or applied. To reduce terminological confusion, Barrett Purcell and Associates suggested that the term "WUE" should be used as an umbrella or generic term including both dimensionless efficiency measures and performance indices having specific units. However, nowadays, the term "water productivity" is used to denote the ratio of net benefits from the agricultural system encompassing crops, forestry, fisheries, and livestock to the amount of water used to produce those benefits (Molden et al. 2003). The parameters considered as input and output for this term also differ at plant, field, and basin level.

We know that the water is delivered from various sources like river, reservoir, groundwater, etc. to the farmers' field through the conveyance system (Passioura 2006). The water is lost due to seepage, leakage, or evaporation during this process (Allen and Pruitt 1986). The efficiency of water conveyance system is expressed as Water Conveyance Efficiency (WCE) which is the percentage of amount of water delivered in the farmers' field by the conveyance system in relation to the amount of water introduced in the conveyance system at the point of diversion from the water source like river, reservoir, etc. (Evett et al. 2001). After application of irrigation water in the farm, some of its proportion is stored in the crop root zone while the rest is lost by processes such as runoff or deep percolation. In this context, the WUE is denoted as water application efficiency (WAE) which is the ratio of the quantity of irrigation water stored in the root zone for crops consumptive use to the amount of irrigation water actually applied in the field (Purcell 1999). The WCE and WAE can be computed using the following equations.



Source : Department of Agriculture, Cooperation & Farmers Welfare

Fig. 15.13 Area covered under sprinkler irrigation in different states of India



Source : Department of Agriculture, Cooperation & Farmers Welfare

Fig. 15.14 Area covered under drip irrigation in different states of India

$$\text{WCE }(\%) = \left(\frac{\text{Water delivered to the farm by conveyance system}}{\text{Water introduced into the conveyance system from the point of diversion}}\right) \times 100$$

$$\text{WAE }(\%) = \left(\frac{\text{Water stored in the crop root zone}}{\text{Water applied in the farm}}\right) \times 100$$

At crop level, the ratio of marketable crop yield or biomass produced to the total crop evapotranspiration during crop growing season is known as crop WUE or crop water productivity with units of kg ha^{-1} mm^{-1} or kg/m^3. If we consider the depth of water applied through irrigation in the field for obtaining the marketable crop yield, then the term WUE is denoted as irrigation WUE or irrigation water productivity. Irrigation WUE and Crop WUE can be calculated using the following equations (Allen et al. 1998):

$$\text{Irrigation WUE }\left(\text{kg ha}^{-1}\text{ mm}^{-1}\right) = \frac{\text{Crop Yield }\left(\text{kg ha}^{-1}\right)}{\text{Water used to produce yield}\left(\text{mm or m}^3\text{ha}^{-1}\right).}$$

$$\text{Crop WUE }\left(\text{kg ha}^{-1}\text{ mm}^{-1}\right) = \frac{\text{Grain Yield }\left(\text{kg ha}^{-1}\right)}{\text{Crop Evapotranspiration (mm)}}$$

15.5 Impact of Climate Change on Water Availability and Water Use Efficiency

15.5.1 Climate Change and Water Availability

The principal consequences of CC on human beings are largely controlled by water (UN-Water 2018) and occur primarily through climate-driven-water-related ecosystem changes (IPCC 2014). Agricultural sector withdrawals account for around 70% of all the available freshwater resources for irrigation and allied activities worldwide (Fischer et al. 2007; Meena et al. 2020a). Thus, it is crucial to consider the impact of CC on availability of water and its use in agriculture to modify net irrigation demands, consumption, and crop water usage. There are numerous ways, in which CC influences water availability as well as its quality. For example, variations in spatial and temporal trends of weather parameters and particularly the variability in amount and intensity of rainfall influence the distributions of surface water as well as the volume of runoff, and thus the recharge of groundwater. By the end of this century, the estimated rise in global temperature ranges between 1.1 and 6.4 °C as compared to the past few decades of previous century, based on the emissions of potent greenhouse gases (GHGs) (Betts et al. 2011). The rise in temperature would lead to greater evaporative losses from open landscapes and open water resources, therefore loss of residual soil moisture, and increased plant transpiration may potentially reduce the availability of water (Yang et al. 2011b; Hipsey and Arheimer 2013). Simultaneously, as a result of CC, the world's hydrological cycle is stepping up to get intensified due to which drier areas are getting drier and wet areas are getting even wetter. The degree of anticipated changes in rainfall varies considerably, based on topography, vegetation, and edaphic factors at both temporal and spatial scale (Bates et al. 2008). On a fairly regular basis, the events of heavy and extreme rainfalls have increased, even in those areas where cumulative rainfall may decrease (Orlowsky and Seneviratne 2012). Such changes will have an ancillary impact on agricultural productivity and output, while atmospheric carbon dioxide (CO_2) has the potential to increase the accumulation of photosynthates as higher as up to 30% in crop plants (Ainsworth and Ort 2010). Nearly 33% of the largest groundwater systems on the planet are in crisis already (Richey et al. 2015). It is reported that almost half of the world's population is residing in the regions that usually have a scarcity of water at least 1 month every year, and around 73% of them are living in the Asian region and by 2050, this figure may rise further (Burek et al. 2016).

15.5.2 Extreme Weather Events and Their Impact on Water Availability

The trajectory of global runoff is getting altered because of higher variability in rainfall and evapotranspiration patterns owing to CC (Milly et al. 2005). It is estimated that by the year 2050, all river basins of India would be facing scarcity of water, except Godavari, Brahamani-Baitarani, Mahanadi, and Narmada (Mujumdar 2008). There is also a likelihood of general reduction in the quantity of available runoff. However, above all, the rate, extent, and magnitude of extreme weather events are intensifying as a result of CC (O'Gorman 2015), which will give rise to the water-related hazards (IPCC 2012; Mazdiyasni and AghaKouchak 2015). Guhathakurta et al. (2011) noticed a rise in the events of extreme precipitation in India due to CC. Mondal and Mujumdar (2015) also analyzed changes in extreme rainfall characteristics over India. This increased rainfall intensity may lead to higher runoff and possibly reduced recharge (MoEF 2004). The severity of droughts and intensity of floods in various parts of India is likely to increase (MoEF 2012; Hirabayashi et al. 2013), which will also alter the dynamics of irrigation resources. The economy, culture, and the environment are affected negatively by drought which ultimately cause significant impacts on human life by influencing aspects such as irrigation water availability, agricultural and horticultural farm production, daily wages and livelihood of labors and farming community, cattle health and production from dairy and poultry, wild habitats, soil fertility, and other edaphic factors like erosion, public health, and safety. Many drought famines during previous centuries have caused millions of deaths in India. Mishra et al. (2019) studied agricultural drought based on soil moisture and station-based climatological data for a period of 1870–2016. They found that India has encountered seven substantial drought spells (1876–1882, 1895–1900, 1908—1924, 1937–1945, 1982–1990, 1997–2004, and 2011–2015) based on their severity, area covered, duration of dry spell, and residual soil moisture since the mid-nineteenth century which are attributable to El Niño–Southern Oscillation (ENSO), which is an important signal of periodic climatic variability. The recent findings showed a substantial rise in the occurrence of drought conditions in India while dry and wet spells alternated over the past decades (Alexander et al. 2006; Kharin et al. 2013; Vinnarasi and Dhanya 2016).

The spatial and temporal variability of precipitation patterns has also been studied by many researchers which suggests that variability will rise in the upcoming decades in India as well as globally (Luo et al. 2014; Priyan 2015; Huang et al. 2018). This is suggestive of severe and substantial occurrences of precipitation during limited ISMR period accompanied by long dry spells. Recharge of groundwater via natural absorption and deep percolation happens just beyond a threshold level of rainfall. As the intensity of rainfall will increase, the amount of runoff as well as runoff coefficient (amount of runoff per unit of rainfall received) will also increase which will hinder the natural groundwater recharge process and have adverse impact on the availability of irrigation water from natural aquifers (Carter 2007; Amarasinghe and Sharma 2008; Shah 2009). This excess runoff will increase the incidences of flooding in Indo-Gangetic plains (MoEF 2004). With an increase of 10–12% in the long-period average (LPA) of ISMR, the quantity of groundwater recharge will improve in Andhra Pradesh and Rajasthan, based on the spatial and temporal distributions of ISMR. Both these states have vast regions of over-exploited groundwater, and this increase in ISMR can be beneficial in recharging groundwater and increasing the availability for irrigation. Although, the rise in temperature and 6–8% decrease in precipitation from LPA in parts of Madhya Pradesh, Gujarat, and Kerala may decrease the groundwater recharge and affect the availability of soil moisture. From the climatic perspective, western and peninsular India are the hot spots of groundwater resources (Shah 2009). So, the net groundwater recharge in any area will be affected by the anomaly and variability in rainfall and the total amount of rainfall received in that area.

The new uncertainty in the availability of groundwater will be seen because CC would impact the quality as well as quantity of groundwater, particularly in the coastal as well as inland regions of India. Certainly, CC due to global warming will lead to an increase in the global sea levels (Allen and Komar 2006). This will happen because of thermal expansion of oceanic water and melting of ice locked water (Meehl et al. 2005). The sea level will rise at an annual rate of 1–2 mm (Unnikrishnan and Shankar 2007; Milne et al. 2009), which may increase up to 26–82 cm by the end of the twenty-first century (Vermeer and Rahmstorf 2009; Rahmstorf 2010; IPCC 2013; Stocker et al. 2013). Glacier melting will have a detrimental impact on hydrological balance in numerous regions of India, which will ultimately modify local weather patterns, forests ecosystem, agricultural productivity, supply of water, human health, livestock, and several other forms of habitats (Allen et al. 2010). The land will inundate because of intrusion of marine, brackish water in the coastal inland regions which will degrade the quality of soil as well as groundwater in these areas. Increasing sea surface temperature (SST) would further lead to a rise in frequency and intensity of cyclonic activities which are often associated with storm surges influencing coastal areas (Wu et al. 2002). The problem of salinity due to intrusion of sea water into subsurface aquifer is already severe in many coastal aquifers, particularly at Gujarat's Saurashtra coast and Tamil Nadu's Minjur coast (Subramanian 2000; Shah 2009), and the most vulnerable ones are Kutch region of Gujarat, Mumbai, and South Kerala (Pathak et al. 2014). Because of excessive groundwater extraction, the water table has dropped to a great depth in Gujarat state, which further escalates the problem of degradation in groundwater quality by allowing percolation and intrusion of the seawater (Subramanian 2000). Around 12% of the landmass of India is vulnerable to floods (Sinha 2003). Escalated incidences and severity of flooding will disturb the quality of groundwater in alluvial aquifers. The deviations in snowmelt runoff from Himalayan regions will affect the recharge as well as the availability of groundwater in Punjab, Haryana, Uttar Pradesh, and Rajasthan.

Anthropogenic changes in climate because of shifting crop and land-use patterns, over-exploitation of irrigation water have caused a decline in the discharge of Ganges over the past three decades, which led to decline in groundwater table as well as a decrease in surface water availability by about 50% (Adel 2002). The agricultural requirement, especially for irrigation, which is a significant portion of India's total demand for water, has become more sensitive to CC. An in-situ change in the climate at the field level may alter the requirement of irrigation. It is estimated that almost all of the irrigated regions in India will need additional irrigation around 2025. There will be a rise of 3–5% and 6–8% in the net global irrigation needs by 2025 and 2075, respectively, as compared to the existing irrigation demands without considering CC (Doll and Siebert 2001). In India, groundwater contributes around 52% for irrigation across the country; thus, it will be a troubling scenario as groundwater is decreasing and irrigation needs are rising because of CC.

15.5.3 Climate Change and Changing Water Demand for Agriculture

Extensive utilization of land due to deforestation, industrialization, intensive agricultural practices, and expansion of agriculture to meet the requirements of the rising population has put extensive pressure on the freshwater resources (Nejadhashemi et al. 2012). The future accessibility of freshwater for humans, livestock feed, farming, and industries is progressively becoming questionable as CC is having its effects. The industrial and domestic water consumption will rise considerably at a much faster pace than agricultural requirement, while agriculture will continue to be the overall greatest consumer. Majority of the rising water demand will be observed in developing countries than developed ones. The FAO has reported a 5.5% rise in extractions of water for irrigation from 2008 to 2050 (Dubois 2011; Alexandratos and Bruinsma 2012), while Burek et al. (2016) have estimated a rise of 23 to 42% in global water requirement for irrigating crops considering 2010 as the base year. The OECD estimated a slight reduction in irrigation water usage over the 2000–2050 periods, citing planned improvements of efficient utilization of water (Rosegrant et al. 2009).

Various studies were undertaken to assess the impact of CC on irrigation. The water resources of Mahanadi river basin were examined by Asokan and Dutta (2008) under the current and projected climate scenario, where they predicted that the intensity of drought during the month of April and flood during the month of September is expected to increase progressively in the near future. They also estimated the water demands and different sectors considering domestic, irrigation, and industry and concluded that the demand of water will increase by 2050, after which a decreasing trend will be noticed due to the expected regulation of population explosion. A study was carried out by Chatterjee et al. (2012) to assess the impact of CC on crop water requirement for Ganga River Basin in West Bengal. While using potato (*Solanum tuberosum*) as the reference crop, they predicted that irrigation water requirement (IWR) will increase from 7 to 8% by 2020, while it may increase from 14 to 15% by 2050. Rehana and Mujumdar (2013) assessed the irrigation requirements of nine locations in India around the Bhadra reservoir command area on a monthly scale and predicted that the annual IWR for paddy, sugarcane, permanent garden, and semidry crops is going to increase in the Bhadra command area. A research was conducted by Parekh and Prajapati (2013) in the Sukhi command area of Vadodara district, Gujarat to evaluate the effect of CC on crop water requirement of rabi (wheat, sorghum (*Sorghum bicolor*), small vegetables, gram (*Cicer arietinum*) and cowpeas (*Vigna unguiculata*)) and hot weather crops (millets, groundnut (*Arachis hypogaea*), maize (*Zea mays*), and small vegetables). Their study shows that crop water requirement of all hot weather crops in all future periods shows an increasing trend as compared to base period 2003–2009. Rabi crops show negligible decrease in crop water requirement in the period 2011–2020 but all crops show considerable increasing water requirement in the period 2021–2030 including the periods 2046–2065 and 2080–2099 as compared to base period 2003–2009. A climate crop water requirement (CCWR) integrated framework was developed by Mohan and Ramsundram (2014) to study the influence of climatic variability on IWR in Manimuthar river basin, Tamil Nadu, India, where they predicted an increase in IWR by 5% from 2010 to 2020.

15.5.4 Climate Change and Water Use Efficiency

Climate is the most crucial determinant of farm production, primarily due to the effects of CC on temperature and water regimes (Lal 2005). The consequences of CC on crop WUE are influenced by numerous ambiguous factors (Carter et al. 1999), one of which is the complexity in global climate model (GCM) projections, mainly concerning climate variability. Further factors involve edaphic properties like residual soil moisture (Eitzinger et al. 2001), soil fertility (Sirotenko et al. 1997), weather variables and rising CO_2 concentration in the atmosphere (Amthor 2001), and vagueness in predictions of crop growth models, which is associated with biophysical interactions. All these variables influence the assessment of the impacts of CC on agricultural production. If scientists minimize the effects of these uncertain and ambiguous factors, a better and clear estimate of the effect of CC on agricultural production may be made. The WUE involving efficient water-saving irrigation techniques depends upon the levels of groundwater and evapotranspiration in that region (Govindarajan et al. 2008). WUE is an important tool for farmers and scientists to assess saving and investments on water, and is conversely associated with vapor pressure (Zwart and Bastiaanssen 2004). The WUE can be substantially increased, if irrigation is minimized and the deficit of water in crops is largely alleviated. The volume of irrigation for optimum crop growth and agricultural output would rise in the areas with the trend of diminishing rainfalls, but this could decrease the WUE of crops. Hence, increasing crop WUE at all levels will be a major challenge (Kijne et al. 2003). The ratio between agricultural production and evapotranspiration is used to compute the crop WUE, and this provides a more detailed understanding of the environmental functioning of soil surface and the resilience of ecosystems, specifically their ability to absorb disturbances and sustain the same function, feedback, response, and sensitivity in changing climate (Walker et al. 2004). In order to develop sustainable management strategies for mitigation and adaptation of future CC, we must understand how climate and agronomic factors influence the crop WUE. Many studies show that crop WUE has a negative correlation with yearly rainfall and air temperature (Zhang et al. 2012, 2015). The conservative WUE of the plant helps them to adapt and acclimatize for drought stresses by enhancing WUE in arid and semi-arid regions (Chen et al. 2010a). Higher temperatures within a certain range raise WUE, but exceptionally high temperature decreases WUE of crops by increasing transpiration from crop plants and evaporation from the surface of the soil (Xiao et al. 2013). However, most of the studies are mainly oriented toward the effect of a single environmental factor (e.g., temperature or rainfall) on crop WUE. Furthermore, the influence of CC on WUE in the agriculture system may be overestimated without taking into account the impact of agronomic resource and management practices. Present agricultural practices, like the choice of crop cultivars, application and distribution of fertilizer and irrigation water, and other farm interventions, may have a dramatic effect on biophysical and biochemical functions and processes within agricultural systems (Chen et al. 2010b) which could potentially change the trends of WUE (Fu et al. 2003). Research on WUE variability under different field management conditions and controlled climates may further enhance our understanding of the underlying mechanisms and dynamics of crop WUE response to CC, which can help in enhanced estimation of the impact of CC on WUE of crops at a regional scale.

15.6 Techniques for Enhancing Water Use Efficiency

The key strategies for enhancing WUE at crop, farm, and basin level are (Pathak et al. 2014):

1. Reducing the gap between the irrigation potential created and utilized

2. Emphasizing on integrated and conjunctive use of rainfall-, surface-, ground-, and waste waters in canal command areas
3. Increasing marketable yield of the crop per unit of evapotranspiration
4. Using efficient water-saving technologies like gravity fed micro-irrigation system, system of rice intensification (SRI), raised bed planting system, laser land leveling, direct-seeded rice (DSR), conservation agriculture, and precision irrigation techniques etc.
5. Development of automated irrigation system for enhancing water productivity
6. Development of site-specific irrigation and fertigation schedules to enhance water and nutrient use efficiency simultaneously
7. Using modern tools and techniques such as geographical information system, remote sensing, integrating water resource development and district irrigation plan for enhancing agricultural water productivity
8. Promotion of rain water harvesting and artificial recharging of groundwater
9. Promotion of water recycle and reuse
10. Development of participatory groundwater management in irrigation
11. Promotion of multiple use of water through integration of water harvesting with efficient irrigation techniques in different farming systems
12. Development of user-friendly decision support system (DSS) for irrigation scheduling on a real-time basis
13. Enhancing crop productivity through integrated watershed management
14. Use of weather forecasting and ICTs for efficient use of water
15. Promotion of awareness of government scheme about conservation of water resources

We have broadly divided the strategies for enhancing WUE into three sections, i.e. techniques to reduce conveyance losses, and strategies related to crop and irrigation management which are briefly discussed further.

15.6.1 Techniques to Overcome Conveyance Losses from Irrigation System

The major conveyance systems to deliver water at farmer's field for irrigation purpose in India are canal network. The conveyance losses in the canal system mainly consist of seepage and evaporation losses. Nevertheless, many researchers quoted that the evaporation loss in canal network is generally not taken into consideration (Xie et al. 1993; ANCID 2000). In India, the seepage loss from canals which are unlined ranges from 0.3 to 0.7 m^3 sec^{-1} per 10^6 m^2 of wetted surface (Indian Standards Measurement 1980). In this context, Badenhorst et al. (2002) revealed that the seepage loss is the major portion of water conveyance loss (98.37%) while about 0.3% of the total tributary is lost due to evaporation. The prevention of water loss through seepage can bring additional area under irrigation. Therefore, for improving WUE, there is also a need to minimize conveyance loss in the canal network system. The techniques to minimize conveyance losses are given below:

15.6.1.1 Lining of Open Channels

The lining of open channels can minimize conveyance losses to a greater extent. Materials preferable for canal lining are generally bricks or rock masonry, concrete as well as asphaltic concrete. However, the lining of open channels is expensive, so that at least upper/head portion of the watercourses should be lined. In this context, Uchdadiya and Patel (2014) found that the seepage losses in canal lining can be reduced by using brick, PCC (plain cement concrete), PCC with LDPE (low-density polyethylene) film to nearly 87.68%, 99.3%, and 99.7%, respectively, in Kim branch canal, Gujarat. The selection of materials used for canal lining depends on locally available materials, their costs, soil parameters like infiltration as well as climatic conditions of sites (Saha 2015). So, the lining of open channels should be carried out to minimize water loss and thus, to improve conveyance efficiency.

15.6.1.2 Maintenance of Earthen Canal

Regular maintenance of earthen canal is required to repair damage caused by rodents and livestock, which can also minimize losses through conveyance and enhance WCE (Prabhata et al. 2001).

15.6.1.3 Use of Low-Pressure Pipes

Irrigation system using buried low-pressure pipes has high conveyance and distribution efficiency of up to 90% as compared to earthen canals and, thus, it can play an important role to minimize conveyance losses (Firouzabadi 2012). However, due to high cost, these are feasible only in regions which are suffering from severe water shortages like Rajasthan and Gujarat.

15.6.1.4 Automation in Canal Irrigation System

Automation in canal system including automated flow-control structures and discharge measurement devices using computer software can help in significantly enhancing the WCE (Shock et al. 2002).

15.6.2 Techniques Pertaining to Crop Management

The WUE is influenced by many factors like crop type or varieties, soil fertility, weed intensity, and so on. So, efficient crop production practices play a crucial role in augmenting WUE. The crop management practices should be such that it reduces the soil moisture loss, increases the availability of soil moisture to the crops, and enhances the ability of crops to maximize the produce or produce per unit of water consumed (Pawar and Khanna 2018). The crop management practices for achieving higher WUE are briefly discussed below.

15.6.2.1 Choice of Crop Type or Variety

In a particular agroclimatic region, the type of crops should be cultivated considering current temperature, rainfall pattern, and length of growing days. The availability of irrigation water and its amount should also be considered while selecting crop type (Kumar et al. 2019). In general, C_4 crops (plants in which the primary CO_2 acceptor is 4-carbon compound) such as maize, pearl millet (*Pennisetum glaucum*), sorghum and sugarcane (*Saccharum officinarum*), have higher crop water productivity than C_3 crops (plants in which the primary CO_2 acceptor is 3-carbon compound) like wheat, barley (*Hordeum vulgare*), oats (*Avena sativa*), pulses and oilseeds because C_4 plants lack photorespiration which increases their photosynthetic efficiency and reduces transpiration ratio (Pawar and Khanna 2018). The crop water productivities of rice, wheat, maize, sugarcane, and cotton (*Gossypium* sp.) are 0.30–0.54, 0.58–2.25, 0.49–1.63, 3.25–7.83, and 0.17–0.40 kg m^{-3}, respectively (Yadav et al. 2000).

The crops or varieties having characteristics such as short duration, deep roots, short stature with erect leaves and awns, low transpiration rate, moderate tillering, extensive adaptability, high photosynthetic efficiency, and short gap between flowering and maturity to avoid the effect of adverse weather conditions are known to have higher crop water productivity (Dahiya et al. 2008). Under rain-fed conditions, the crops like mustard (*Brassica* sp.), gram, barley, flaxseed (*Linum usitatissimum*), and safflower (*Carthamus tinctorius*) can be grown in Northern India whereas cotton, sorghum, and safflower in Deccan plateau and Southern India while flaxseed and safflower crops are suitable for eastern India (Singh et al. 2014). Many leguminous crops such as gram, pigeon pea (*Cajanus cajan*), black gram (*Vigna mungo*), green gram (*Vigna radiata*), and beans (*Phaseolus vulgaris*) can be cultivated under rain-fed regions (Singh et al. 2008). The varieties having higher crop water productivity should be cultivated for conserving water resources. Few examples of such varieties in India are given in Table 15.2.

Table 15.2 Crop varieties having higher crop water productivity

Crop	Variety	References
Wheat	HUW 234, Lok 1, HD 2987, WH 1080	Behera et al. (2002); Shivani Verma et al. (2003); Maheswari et al. (2019)
Rice	Sahbhagi Dhan, DRR Dhan 45, Naveen, Anjali	Maheswari et al. (2019)
Maize	Pusa Hybrid Makka 1, HM 4, DHM 121	Maheswari et al. (2019)
Sorghum	Varsha, CSV 18, CSH 15R	Chand and Bhan (2002)
Chickpea	Avarodhi, Vijay, Vikas	Singh et al. (2004)
Mustard	Vaibhav, SEJ 2	Panda et al. (2004); Awasthi et al. (2007)
Pearl millet	HHB 67–2, HHB 94, HHB 117	Kumar et al. (2003); Rathore et al. (2008)

15.6.2.2 Cropping Pattern, Plant Population, or Method of Planting

Cropping pattern, plant population, and planting method determine the solar energy or light interception, evaporation, rooting pattern, uptake of soil moisture, and crop yield which ultimately affects the WUE (Singh et al. 2014). The optimum cropping pattern, plant population, or method of planting for effective utilization of water depends upon the crop type. For instance, cultivation of pearl millet crop in 45 × 12 cm^2 spacing resulted in higher WUE as plants were able to utilize water and nutrients properly at this plant density (Rathore et al. 2008). Similarly, sowing of cotton crop in paired rows with 90 × 105 cm^2 spacing had higher crop water productivity than standard plant spacing of 120 × 90 cm^2 (Ghadage et al. 2005). Planting of chickpea crop on raised beds had 16–17% higher WUE than flat beds (Pramanik et al. 2009). The cultivation of wheat crop in furrow irrigated raised beds (FIRBs) planting system performed better than flat sowing (Jat et al. 2005). Plant density can be increased in humid regions where precipitation is more than evapotranspiration, but should be decreased in the semi-arid areas so that plants could efficiently utilize the available water. Singh et al. (2003) reported that hiking the plant population by increasing the seed rate from 140 to 205 kg ha^{-1} and decreasing the row spacing from 22 to 15 cm in the late-sown wheat crop can improve the crop WUE. Several researchers reported that planting of crops such as wheat, pearl millet, green gram, and soybean (*Glycine max*) on raised beds and applying water in furrows can save 25–30% of irrigation water which increases WUE (Jat and Gautam 2001; Parihar 2004; Kaur 2006; Zhang et al. 2007; Mahey et al. 2008). Cultivation of rice crop by direct-seeded method can also save an ample amount of water and enhance crop water productivity (Gill et al. 2006). Singh and Mahey (1998) observed that sowing of sunflower (*Helianthus annuus*) crop in Southern side of ridges having East-West direction in sandy-loam soil resulted in higher crop water productivity due to increased yield caused by higher temperature which hastened the germination rate of sunflower seeds, increased leaf area index, and dry matter accumulation.

15.6.2.3 Sowing Time

Sowing time of crop is a crucial non-monetary input which can effectively determine crop yield (Sihag et al. 2015; Abhilash 2016; Kumar et al. 2017b; Meena et al. 2017) and WUE. Crops should be sown at optimum time so that it can avoid moisture and heat stress during critical growth stages like flowering and grain filling. For instance, shifting the paddy transplantation date in Punjab from 1st June to 21st June can save about 100 mm of water against evapotranspiration loss. Similarly, higher WUE was found in sunflower sown in January than the February sown crop due to early maturity, which minimized the water use (Hira 2004). Pal et al. (1996) observed that timely sown wheat crop (24th November) produced higher yield and WUE by 27% and 18%, respectively, than late planted wheat crop (18th December). A similar finding was also reported by Panda et al. (2004) who said that delayed sowing of mustard crop beyond 16th October significantly reduced its yield and thereby WUE.

15.6.2.4 Intercropping

In intercropping, overall WUE is improved because crop yields are similar to the sole crop but comparatively lesser amount of irrigation water per crop is applied (Singh et al. 2014). Higher WUE in intercropping is reported by several researchers such as maize + potato (Bharati et al. 2007), pearl millet + cowpea and pearl millet + green gram (Goswami et al. 2002; Layek et al. 2018), maize + sorghum (Sani et al. 2011), wheat + maize (Yang et al. 2011a), pigeon pea + green gram (Kumar and Rana 2007), and many more.

15.6.2.5 Crop Nutrition

Soil moisture condition influences the activities of plant roots to absorb nutrients from the soil as the highest uptake of nutrient occurs at low soil moisture suction or field capacity (Singh et al. 2014). Good availability of nutrients either from inorganic fertilizers or from its combination with organic manures and biofertilizers can effectively increase crop yield as well as crop resistance against diseases and insect-pest attack, which ultimately affects the WUE positively (Gupta and Kumar 2018). Kumar et al. (2003) reported that with increasing the dose of nitrogen from 0 to 150 kg ha^{-1} in pearl millet, the WUE also increased. Rani et al. (2019) reported that with increase in nitrogen dose up to 120 kg N ha^{-1} in wheat, the water productivity increased significantly. Phosphorus fertilizers, along with nitrogen enhanced WUE under moderate water stress condition due to increased root growth, root water potential, and grain yield (Liang 1996; Zhang and Li 2005). Potassium fertilization is also reported to play a role in improving drought resistance as well as WUE (Li et al. 2001). Singh et al. (2004) reported that application of sulfur at the rate of 40 kg ha^{-1} in chickpea (*Cicer arietinum*) resulted in maximum WUE. Kumar and Rana (2007) revealed that the pigeon pea crop produced highest equivalent yield, nutrient uptake, and crop water productivity by applying 40 kg P_2O_5 ha^{-1} + 25 kg ha^{-1} along with phosphate solubilizing bacteria. Similarly, Sarma et al. (2005) reported that wheat crop showed maximum crop water productivity under application of 187.5 kg N ha^{-1} + 10 t FYM (Farmyard manure) ha^{-1} + *Azotobacter* culture. The similar finding was also reported in black gram and green gram with application of biofertilizers and chemical fertilizers (Jangir et al. 2016; Varma et al. 2017). Thus, balanced and integrated nutrient management is very crucial for enhancing crop water productivity (Kakraliya et al. 2017a, b; Sharma et al. 2019).

15.6.2.6 Seed Priming

The soaking of seeds in water for overnight followed by surface drying before sowing is found to hasten the maturity time and improved productivity and WUE in many crops like maize, wheat, chickpea, and lentil (*Lens culinaris*) as this process reduces the need of pre- and post-sowing irrigation (Rao and Phillips 1993; Rashid et al. 2002; Ali 2004). Seed inoculation of leguminous crops, i.e. chickpea with *Rhizobium* and phosphate solubilizing bacteria is reported to improve WUE than single or no inoculation (Singh et al. 2004).

15.6.2.7 Mulching

Mulching is a practice to cover soil surface with materials such as straw or crop residues, and plastic film which significantly reduces the evaporation from soil along with other benefits like moderating soil temperature variation, protecting soil aggregates from beating action of rain drops, reducing runoff loss, and controlling weeds (Singh et al. 2014). The soil evaporation rate decreases with increasing the quantity of crop residues on the surface (Gill and Jalota 1996; Prihar et al. 1996). Sauer et al. (1996) also reported that crop residue mulch reduced the evaporation loss from soil by 34–50%. Pandey et al. (1988) reported that by application of straw mulch in pearl millet crop cultivated under rain fed conditions, the grain yield and WUE improved significantly than without mulch treatment.

Plastic mulch is used to reduce soil evaporation along with increasing soil temperature, which influences the crop growth, especially during the winter season. Rashidi et al. (2009) reported that application of black plastic mulch in timely or late-sown tomato (*Solanum lycopersicum*) crop increased the yield as well as WUE as compared to the crop grown without mulch. Nalayini et al. (2006) also reported that by application of black plastic mulch in cotton crop, the WUE was increased to 43.2 kg ha^{-1} cm^{-1} as against 16.6 kg ha^{-1} cm^{-1} in without mulch treatment. Plastic mulching is generally applied to cash crops due to high economic cost and difficulty in its removal and disposal. Another type of mulching known as vertical mulching is practiced in Vertisols or black soils in which stubbles are filled in trenches of size 30×60 cm^2 dug at 5–10 m interval. Vertical mulching increases the water intake capacity and infiltration rate of Vertisols. Mulching is most suited from low to medium rainfall areas to conserve soil moisture.

15.6.2.8 Tillage Practices

Tillage is a mechanical manipulation of soil for producing seed-bed condition conducive to seed germination and root growth. It influences the soil structure, infiltration characteristics, distribution of soil pores, soil moisture extraction pattern, and movement of soil water and dissolved nutrients (Dahiya et al. 2018). It helps in controlling weeds and soil-borne diseases and other insect pests. Shallow inter-row tillage reduces soil evaporation by breaking the soil crust, continuity of capillary pores, and closing the soil cracks. Off-season tillage, i.e. tillage between two crop seasons is done to open the soil for soaking rainfall water along with destroying insect pests and controlling weeds. Deep ploughing is done to break the plough pan or hard-pan in the subsoil. Deep tillage at the frequency of every 3–4 years after harvesting of the crop significantly improves soil infiltration and moisture storage capacity, which influences the WUE (Bhan 1997). Deep tillage with crop residue mulching can reduce the runoff and erosion by 50% and 90%, respectively in comparison with conventional tillage without mulching (Jin et al. 2006).

Conservation tillage involving minimum soil disturbance along with residue retention is nowadays promoted by scientists to enhance WUE along with other benefits like saving of cost, energy and labor, soil carbon sequestration, improvement of soil quality, and conservation of natural resources, which is crucial for attaining agricultural sustainability and food security (Busari et al. 2015).

Conservation tillage can be performed by various ways, viz. zero or no tillage, reduced or minimum tillage, permanent raised beds, and contour tillage. In no or zero tillage, the soil is disturbed only at the area of sowing through no-till seed drill while the remaining space is kept undisturbed. In minimum or reduced tillage, only primary tillage operations are performed. In permanent raised beds method, raised beds are constructed before starting of the cropping season, which is kept undisturbed during subsequent cropping cycles. In contour tillage, the soil is tilled across the slope, which obstructs the free flow of runoff and provides more opportunity time for infiltration of runoff water. Zero tillage is generally practiced in the wheat crop after rice in Indo-Gangetic plains of India. Approximately 20–35% of irrigation water can be saved in the wheat crop through zero tillage as compared to the conventional tillage (Mehla et al. 2000; Gupta et al. 2002). This practice saves pre-sowing irrigation in the wheat crop as the residual moisture is available after harvesting of paddy crop (Gupta et al. 2002). This method also made it possible to sow and harvest wheat crop earlier, which further eliminated the use of one or more late-season irrigations. Jat et al. (2013) experimented on maize-wheat cropping system in sandy-loam soil where permanent raised bed treatment showed 16% higher WUE than conventional tillage. The IWR in permanent raised beds and no-till flat treatment was 24.7% and 10.8% less than the traditional tillage treatment. In pigeon pea-wheat cropping system, conservation tillage had higher WUE compared to conventional tillage (Das et al. 2016).

15.6.2.9 Weed Control

Weeds are the unwanted plants that grow in the crop field and compete with the main crop for inputs like light, water, and nutrients which adversely affect the growth of the main crop (Singh et al. 2014; Dahiya et al. 2017). Therefore, efficient control of weeds is very crucial for enhancing WUE by reducing transpiration loss from weeds along with improving the availability of other inputs to the main crop, which increase the crop yield. Nadeem et al. (2007) reported that manual weeding resulted in maximum WUE in the wheat crop, which was statistically similar to weed control by application of post-emergence herbicides in comparison with the uncontrolled treatment. Similar findings were reported by Singh et al. (2004) in chickpea and Reddy et al. (2008) in pigeon pea. The control of weeds through integrated use of mechanical, chemical, and biological methods should be adopted as it does not harm the environment and helps in maintaining sustainability.

15.6.2.10 Irrigation Management

Crop types and varieties have varied water demands depending upon their physiological processes, genetic make-up, weather, and soil type (Ali and Talukder 2008). So, appropriate irrigation management is needed to meet the crop water demands along with enhancing crop water productivity. There are various techniques of irrigation management for improving WUE which are briefly discussed below:

Critical Crop Growth Stage Approach

If limited irrigation water is available to the farmers, then they can apply irrigation at moisture-sensitive stages known as critical growth stages because the water stress at these stages may lead to irreversible yield loss (Kramer 1969). Panicle initiation and flowering are critical stages in cereals, but in pulses, flowering and pod development stages are critical (Gupta 1975).

Deficit or Limited Irrigation

In this method, lower water amount than the plant requirement is applied through irrigation. It can be done by many ways via reducing the irrigation depth, alternate wetting and drying, skipping irrigation at insensitive stages, wetting only crop root zone, or decreasing frequency of irrigation (Ali and Talukder 2008). It reduces evapotranspiration and improves water productivity (Liang et al. 2002). It makes plants tolerant to water stress as hardening process by physiological adjustments that take place in plants when they are subjected to gradual water stress (Turner 2004).

Furrow Irrigated Raised Bed (FIRB) Planting Technique

In this technique, the crops are planted on raised beds having a width of 40–70 cm and height of 15–20 cm depending upon the crop type (Jat et al. 2005). The width of the furrow is 25–30 cm. This method is reported to save 25–40% of irrigation water along with saving of other inputs like seeds, fertilizers, and herbicides in comparison with flat planting (Fahong and Xuqing 2004; Dhindwal et al. 2006; Kumar et al. 2010; Singh et al. 2014). Jat et al. (2005) reported that this method also provides ample opportunities for crop diversification especially in Indo-Gangetic plains of India apart from saving inputs and resources.

Irrigation Water Management in Rice Crop

Rice is the staple food of India, being cultivated in approximately 44.4 M ha of area. Rice crop is highly water-intensive as it requires about 90–250 cm of water for its growth and approximately 2500 L of water for producing 1 kg of grains (Bouman 2009). Therefore, enhancing WUE in rice is utmost important for saving our water resources. The following methods can increase WUE in rice:

Alternate Wetting and Drying In this method, irrigation water having 5 cm of ponding (wetting) is applied to rice crop after 3–4 days of receding ponded water (drying or field capacity). This method saves about 20–30% of irrigation water without influencing the crop yield (Sandhu et al. 1980; Sarkar et al. 2002).

Direct Seeded Rice (DSR) DSR is the method of sowing dry or sprouted rice seeds directly in the field rather than the conventional method of transplantation of seedlings. This method can produce equivalent yield to puddled transplanted rice provided the field is leveled properly, and weeds are controlled efficiently. This method saves about 20–25% of irrigation water and, thus, increases crop water productivity (Tabbal et al. 2000; Jat et al. 2005; Chahal et al. 2007). Apart from increasing WUE, this technique also results in early maturity of rice, and saving of inputs like labor, energy, and fertilizers.

System of Rice Intensification (SRI) SRI was originated in Madagascar, which provides several benefits such as saving of seeds, water, and fertilizers along with higher grain yield in comparison with the traditional method of rice cultivation. In the SRI technique, the rice seedlings are transplanted at two-leaf stage, and only one seedling is planted per hill in a wider square-shaped pattern having 25 × 25 cm^2 spacing. This method is reported to save up to 50% of irrigation water with WUE of up to 91% than traditional transplanted rice (Reddy et al. 2005; Zhao et al. 2010).

15.6.2.11 Anti-Transpirants

Anti-transpirants are materials or chemicals which are applied on transpiring surfaces of the crop to reduce transpiration loss. Anti-transpirants are of four types depending upon their mode of action (Singh et al. 2014) (Fig. 15.15).

Stomatal Closing Type Fungicides and herbicides like phenyl mercuric acetate (PMA) and atrazine, respectively, in low concentration serve as stomatal closing type anti-transpirants but they also reduce the photosynthesis rate simultaneously (Singh et al. 2014). Researchers observed that PMA is more effective to reduce the transpiration rate.

Film-Forming Type Film-forming anti-transpirants like mobileaf, hexadecanol, and silicone form a thin layer on the leaf surface and make it resistant to the passage of water vapors (Singh et al. 2014). Nevertheless, its use is limited due to simultaneous reduction in the rate of photosynthesis.

Reflectant Type These types include 5% kaoline spray and celite (diatomaceous earth product) which increases leaf reflectance. They also reduce the leaf temperature and vapor pressure gradient from leaf to atmosphere, which further helps in reducing the transpiration (Singh et al. 2014).

Growth Retardant Type Growth retardant type like Cycocel reduces shoot growth, induces stomatal closing, and increases the growth of roots which enable the plant to resist water stress in drought conditions (Singh et al. 2014).

However, the use of anti-transpirants to save crops in severe moisture stress conditions is very limited, because they reduce the photosynthesis rate, and are not much economical and practical. They are mainly useful for reducing the transplantation shock of nursery plants (Singh et al. 2014).

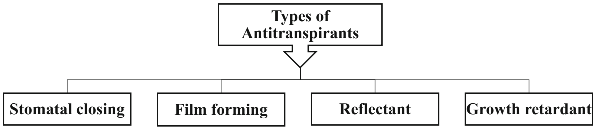


Fig. 15.15 Types of anti-transpirants

15.6.2.12 Windbreaks and Shelterbelts

The increase in wind velocity increases the atmospheric evaporative demand which in turn increases evapotranspiration (McMahon et al. 2013). Windbreaks are the structures, which break the flow of wind and reduce the wind velocity. Shelterbelts serve the same purpose, but they are composed of rows of trees or shrubs. Both windbreaks and shelterbelts are very useful for increasing air resistance to water vapor transfer and thereby, help in reducing transpiration rate from the crops and evaporation from the soil along with protecting the soil from wind erosion (Kort 1988). Windbreaks and shelterbelts should be installed or planted in the direction perpendicular to the direction of prevailing winds. Ogbuehi and Brandle (1981) reported that windbreak enhanced the yield and WUE in the soybean crop. Wind strip cropping, which consists of planting tall crops with small crops, alternately across the direction of prevailing winds is also found to be effective in conserving moisture in water scarcity areas (Bravo and Silenzi 2002).

15.6.3 Techniques Pertaining to Irrigation Application System

In India, the traditional and widely used irrigation method is surface irrigation such as flooding, border, check-basin, and furrow irrigation. However, the significant constraints of these surface irrigation methods are poor irrigation efficiency (35–40%) (Burt et al. 1997). Therefore, there is a need for paradigm shift from these traditional irrigation methods to the improved irrigation methods. The integration of these improved methods can help in precision or site-specific irrigation. The improved irrigation methods are discussed below:

15.6.3.1 Alternate Furrow Irrigation Method

In an alternate furrow irrigation method, irrigation water is applied to alternate furrows or only one side of the crop rows. This method is reported to enhance crop water productivity as the amount of water lost through soil evaporation is reduced (Stone et al. 1982; Davies and Zhang 1991; Einsenhaver and Youth 1992) as compared to commonly used every furrow irrigation method. Approximately 25–50% of irrigation water is saved in this method than every furrow irrigation method without significant reduction in crop yield (Kang et al. 2000; Golzardi et al. 2017; Eba 2018). This method is suitable for saving irrigation water and improving WUE in arid, semi-arid, and humid climate.

15.6.3.2 Wide Spaced Furrow Irrigation

In this method, furrows are 2–5 m apart and two or more rows of crops are present on the ridges. Irrigation water is applied in the furrows. This method reduces evapotranspiration and saves 20–50% of irrigation water as compared to every furrow irrigation method (Stone et al. 1982; Stone and Nofziger 1993). This method is suitable for fine-textured soil as they have both lateral and vertical water movement, which is absent in the case of coarse-textured soil (Stone et al. 1979).

15.6.3.3 Surge Irrigation

In this method, irrigation water is not applied continuously, but intermittently in a series of "on" and "off" pulses at constant or variable rates (Bahu et al. 2005). This method is suitable for Vertisols having swelling and shrinking characteristics on wetting and drying (Stringham 1988). This method ensures uniform infiltration by reducing the soil aggregate breakdown in Vertisols, saving of irrigation water, and improvement of irrigation efficiency by 20–30% and WAE of up to 85% resulting in higher crop water productivity (Mintesinot et al. 2007; Horst et al. 2007; Valipour 2013).

15.6.3.4 Porous Pots Irrigation

Porous pots irrigation is performed by a series of underground interconnected unglazed porous pots with their openings above the ground to fill them by water (El Awady et al. 2003). These porous pots maintain moisture near plant roots, similarly to a drip system but more economical regarding costs. In the rural context, this technique was most popular during the eighteenth century, especially in Latin America and the Caribbean, and can be used nowadays by poor farmers in water-scarce area (Cardenas and Dukes 2012).

15.6.3.5 Pressurized Irrigation System

Pressurized irrigation system was developed for efficient utilization of water, energy, and nutrients in soils. This system is capable of reducing the irrigation cost, electricity consumption, and fertilizer usage by 20–50%, 31%, and 7–42%, respectively (PMKYS 2015). The pressurized irrigation system includes sprinkler irrigation, central pivot sprinklers, and drip irrigation. In 2018–19, the targeted area covered under micro-irrigation in Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) was 11.58 lakh ha out of which 5.75 and 5.83 lakh ha was under drip and sprinkler, respectively (PMKYS 2020). The collective research from various research institutes in India results in reductions in water use and yield increment with drip system in the range of 30–60% and 20–50% respectively, for various crops, including cotton, sugarcane, grapes, tomatoes, and bananas (Indian National Committee on Irrigation and Drainage 1994; Sivanappan 1994, 2009; Van der Kooij 2009). Gleick (2002) also reported that the shifting from conventional irrigation to drip irrigation has increased overall water productivity by 42–255% for crops like banana (*Musa* sp.), cotton, sugarcane, and sweet potato (*Ipomoea batatas*) in India. Therefore, the pressurized irrigation system has great potential to enhance agricultural water productivity in India. Apart from it, there is a need to give more emphasis on the utilization of solar energy. Thus, a solar operated micro-irrigation system can play an important role to save energy and reduce carbon emissions in agriculture. The main constraint in its adoption by the Indian farmers is high initial cost of installment. This constraint can be removed by providing subsidy to the farmers for its purchase and installation by the government (Figs. 15.16 and 15.17).

Fig. 15.16 Sprinkler irrigation

Fig. 15.17 Control head and setup of drip irrigation system

15.6.3.6 Variable-Rate Irrigation

Variable-rate irrigation provides site-specific water and nutrient management and helps in enhancing overall WUE. Either speed or zone control can perform variable-rate irrigation. It reduces pumping cost which helps in reducing GHGs emissions (Trost et al. 2013), energy savings (Hedley et al. 2009) and also reduces surface runoff as well as deep percolation losses (Daccache et al. 2015; Gonzalez Perea et al. 2018). The automatic zone-specific irrigation with wireless sensor network was also developed by Goumopoulos et al. (2014), which helps in monitoring soil, crop, and weather status in a field. It has excellent potential to achieve integrated watershed management.

15.6.3.7 Sensor-Based Irrigation System

Irrigation scheduling plays a vital role in improving WUE through different irrigation methods. Irrigation scheduling helps to quantify the time and amount of irrigation in fields. Scientifically irrigation scheduling is done by the gravimetric method, which is tedious and time-consuming. In the current scenario, soil moisture sensors measure in-situ moisture in fields and helps in irrigation scheduling (Thompson et al. 2007) as well as precision agriculture (Skierucha and Wilczek 2010; Kumar et al. 2017c). In this context, many soil moisture sensors like tensiometers, resistance blocks, TDR (time domain reflectometry), FDR (frequency domain reflectometry), watermarks, and Neutron probe have been used for irrigation scheduling to monitor and measure in-situ soil moisture (Leib et al. 2002, 2003; McCready et al. 2009; Francesca et al. 2010). Some sensors like TDR and FDR give volumetric moisture content, whereas tensiometers and watermarks measure soil matric potential (Fig. 15.18). Nevertheless, in case of orchards due to deep-rooted system, it is challenging to use soil moisture sensors for irrigation scheduling and canopy sensors like sap flow meter, LVDT (linear variable differential transducer), pressure chamber apparatus, and digital lux meter, infrared thermometer, thermal camera, IRGA (Infrared Gas Analyzer), etc. are most preferable and measure plant water status directly or indirectly (Fig. 15.19). Apart from it, when soil moisture sensors integrate with canopy sensor like an infrared thermometer, it can improve the reliability of irrigation scheduling decisions (Kisekka et al. 2014). They help the irrigators to decide on irrigation scheduling. In this context, Dukes et al. (2010) revealed that the tensiometer-based irrigation scheduling reduces IWR in the range of 40–50% in tomato field, but they require frequent maintenance. Apart from it, wireless sensor array also helps in real-time irrigation scheduling (Vellidis et al. 2008).

15.6.3.8 Decision Support Systems

It helps the decision-makers to solve complex problems in a better and faster way by providing a large number of alternatives. It has been developed for various applications like crop water management, yield prediction, irrigation scheduling, and computer-aided mapping. In this context, software related to soil water balance

Fig. 15.18 Soil moisture sensors for irrigation scheduling


LVDT

Pressure Chamber Apparatus

Sap Flow meter

Digital Lux meter

Fig. 15.19 Plant-based sensors and instruments for irrigation scheduling

like CROPWAT, IrriSatSMS, IrriSat, and PILOTE (Smith 1991; John et al. 2009; Urso et al. 2013) helps in irrigation scheduling of different crops. DRIPD (Rajput and Patel 2003) was developed for different design parameters estimation of drip irrigation system. Kumar et al. (2017a) developed DSS and integrated it with tensiometer-based soil moisture sensor for real-time irrigation scheduling in potato crop. Adefisan et al. (2007) developed a model for West Africa (WAIRWS), which helps in irrigation scheduling and its requirement. In the case of conventional irrigation, DSS for furrow and border irrigation was also developed by McClymont (2007). The dynamic DSS for farm water management was also developed by Flores et al. (2010) which could improve furrow irrigation efficiencies up to 95.89% (application efficiency) and 94.61% (total distribution efficiency). Thus, DSS derived irrigation scheduling helps in precision water application and supports “more crop per drop’ paradigm.

15.6.3.9 Internet of Things-Based Smart Irrigation System

Internet of Things (IoT), i.e. interconnection between sensors or computing apparatus through the internet. The automated irrigation system like IoT-based smart irrigation system consists of seven main components discussed below (Rawal 2017):

Field Data Collection Device Incorporated with Relay Switch The data is collected from various wireless sensors installed in the field such as soil moisture sensors and soil thermometer, air humidity and temperature sensor, ultraviolet light radiation sensor (Kim and Evans 2009). The data is fed into Arduino-Uno (microcontroller) which is further connected to a mini and open-source Linux computer known as Raspberry-Pi. It is connected with relay switch to control water supplying motor pump.

Web Service for Gathering Field Sensor Data The data collected from field data collection device is connected to web service.

Web Service for Online Agrometeorological Data Collection This system collects weather data like temperature, humidity, cloudiness, and precipitation, from various weather forecasting web portals for forecasting. The collected data is further used in soil moisture prediction algorithm (Tomaszewska et al. 2012).

Algorithm of Soil Moisture Prediction The algorithm is developed for soil moisture prediction based on sensors data installed in field and weather forecasting data which is required for deciding irrigation scheduling (Rawal 2017).

Responsive Web-Based Interface for Real-Time Monitoring The interface using web service is developed to monitor field sensors data on real-time basis, soil moisture prediction for upcoming few days, and rainfall data for deciding irrigation scheduling.

Web Service to Monitor Water Motor This controls Raspberry-Pi, which starts or stops the water motor through a relay switch.

IoT Enabled Water Pump The pump is linked with a relay switch, which is further accessed by internet through a web service interface. This web service interface is used to manage the irrigation from remote areas either automatically through DSS software or manually through a control unit (Rawal 2017).

This IoT-based smart irrigation system helps in regulating the irrigation amount and timing from the pressurized irrigation systems through the internet. This system helps automatically switch on/off the irrigation system from remote areas which reduces the drudgery of farmers, saves time and water (Subramanian 2000; Kumar et al. 2016a). The WUE of this system is more than 90% (Parameswaran and Sivaprasath 2016; Kumar et al. 2016b). In this way, this system helps in precision or site-specific irrigation, which minimizes the loss of water and improves crop productivity, which ultimately produces “more crop per drop.” However, this system is economically feasible only for large farmers in India (Fig. 15.20).

The above-discussed technologies and practices can be adopted by the farmers depending upon the resources available and level of their knowledge to enhance the WUE so that “more crop per drop” can be produced.

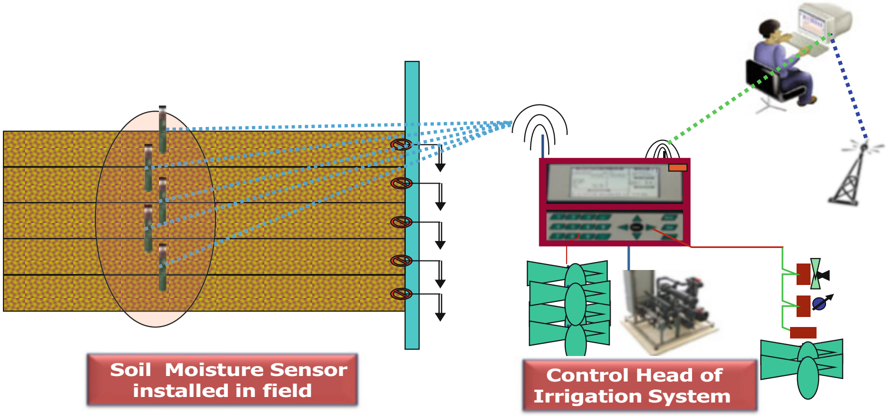


Fig. 15.20 Layout of IoT and sensor-based smart irrigation system

15.7 Policy Instrumentation

Government of India has launched several schemes for enhancing WUE. Recently, "*Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)*" was launched on first July 2015. The main objectives of PMKSY program are the improvement of on-farm WUE, expansion of the irrigated area, promotion of precision irrigation, and sustainable water conservation technologies with the goal of "Per drop more crop," i.e. improving crop water productivity and "*Har Khet ko Paani,*" i.e. irrigation in every field (PMKYS 2015). Micro-irrigation is a substantial component of this program. The PMKSY program helped in increasing the area under micro-irrigation such as sprinkler and drip irrigation. However, there are some constraints in its successful adoption by the farmers like complicated application process for getting loans, delay in getting funds and loans, erratic electricity supply, unavailability of soluble fertilizers, choking of laterals and drippers, high capital investment, damage of laterals by rodents, and inadequate follow-up services by drip agencies (Meti 2012). So, for its proper implementation, the government should focus on removing these constraints. Along with that, micro-irrigation system should be popularized among farmers not only as a water-saving technique, but also as a technique to increase crop productivity along with saving of inputs like fertilizers and electricity. Funds for micro-irrigation should be disbursed based on crop productivity and the extent of water scarcity in a region.

The CC is also affecting our water resources and WUE; therefore, policies are also formulated by the Indian government considering the adaptation and mitigation of CC and variability. National water mission under National Action Plan for CC was launched on 30th June, 2008 with five main goals, i.e. increasing WUE by 20%, comprehensive water database in public domain and assessment of effect of CC on water resources, promoting state citizens to take action for conservation of water, augmentation and, conservation, particular emphasis on vulnerable zones in over-exploited areas, and, promotion of integrated management of water resources at basin level (NWM 2011). Another scheme called as National Mission for Sustainable Agriculture has been launched with four main activities, viz., Rain-fed Area Development, on-farm water management, soil health management, CC and sustainable agriculture to enhance the WUE under CC scenario (NMSA 2012; Meena et al. 2020a, b). Adequate implementation of the watershed development program is crucial to facilitate the surface and groundwater recharge. In this pursuit, Jal Shakti Abhiyan was launched by the government of India from 1st July to 15th September, 2019 (extended up to 30th September 2019) and then from 1st October, 2019 to 30th November, 2019 for states receiving the North East retreating monsoons (PIB 2019a). The vital water conservation interventions under this scheme were water conservation and rainwater harvesting, renovation of traditional and other water bodies/tanks, reuse of water and recharging of structures, watershed development, and intensive afforestation. The schemes launched by the government of India for dealing with the problem of water crisis by enhancing WUE are apparent, but effective implementation and timely as well as adequate disbursement of funds is required for getting the impact of these schemes at ground level.

Some state governments like Punjab, Haryana, and Telangana, etc. are providing free electricity to farmers, which has led to the over-exploitation of groundwater and decline in water table (Dhawan 2017). So, instead of providing free electricity to farmers, these state governments should invest more in water efficient irrigation technologies like micro-irrigation. There is a need to increase awareness among farmers about water crisis and strategies that they can adopt to enhance WUE. For dealing with the problem of erratic power supply to the farmers' field, the government of India has launched a new scheme for farmers for installation of solar pumps and grid-connected solar power plants to encourage farmers to use solar pumps for irrigation (Dhawan 2017). The use of solar energy for generating electricity is a sustainable and environment-friendly solution for our power crisis, along with reducing the carbon footprint. Water pricing can also be a solution to encourage farmers to avoid wastage of water and to adopt practices or techniques, which enhance WUE.

The government should focus on setting up a piped system to connect dams, canals, and micro-irrigation system so that WUE could be increased from 40 to 90%. The government should also promote famers to substitute water-intensive crops like rice and sugarcane with less water demanding crops, especially in the areas, which are on the verge of water crisis. The schemes for diversification of crops and its appropriate marketing should be formulated. Infrastructure for providing irrigation advisory through messages to the famers should be established based on data collected about the soil moisture content, crop water requirement, or upcoming weather conditions through remote sensing approach or from various sources. Precision irrigation can also be promoted for large farmers, corporate farming ventures, and co-operative farming through farmers associations. Adequate skills and training along with appropriate infrastructure for its installation should be imparted by the government to encourage farmers to adopt precision irrigation.

15.8 Conclusions

The availability of water in agriculture is declining due to increased demand from domestic and industrial sectors resulting from increasing population pressure. CC is also leading to uncertainty in water availability and water productivity. So, the adoption of efficient water management practices or technologies in agriculture is the need of the hour. WUE can be increased from crop, farm, and basin level so that the objective of more marketable crop yield from each drop of water utilized, i.e. "more crop per drop" could be attained. The WUE can be increased by minimizing conveyance losses through the proper lining of the conveyance channels. Various crop management practices like the selection of crop or variety, sowing time, planting pattern, method of irrigation, fertilizers, and weed control are beneficial for increasing crop water productivity at field level. The efficiency of irrigation system can be enhanced by adopting improved irrigation systems like micro-irrigation, variable rate irrigation, scheduling of irrigation through soil and crop sensors. DSS can also assist farmers in deciding about irrigation scheduling and policy makers to devise advisory for irrigation scheduling. IoT-based smart irrigation system for precision irrigation should also be promoted, especially among corporate farming ventures or large farmers. The government of India is launching several policies in achieving the target of "more crop per drop" considering the impact of CC and variability. The effective and ground level implementation of such policies with co-operative efforts of government, bureaucrats, corporates, and famers is required.

15.9 Future Perspectives

Various technologies or strategies are available to enhance WUE in India, which we have discussed in this chapter. Nevertheless, still more research efforts are required to be conducted in the area of potential utilization of multi-source or multi-quality water such as usage of treated water from the sewage treatment plant, saline water, or recycled water for irrigation purpose. Further research is required to make micro-irrigation or precision irrigation system economically feasible, especially for small and medium farmers. Suitable crops and its management practices should be formulated to cultivate crops in drought-prone and flood-prone areas. Scientists should develop new varieties having tolerance to flood, drought, and water stress. It is projected that our country may face a water crisis in the near future; so, the focus should be on increasing the quantity of water through desalination of saline water through the development of low-cost technology.

References

Abhilash (2016) Growth and radiation use efficiency of Basmati rice (*Oryza sativa* L.) varieties under different transplanting environments. Agricultural meteorology master's thesis, CCS Haryana Agricultural University, Hisar, Haryana, India

Adefisan EA, Gbuyiro SO, Bayo JO (2007) Development of irrigation requirement and water scheduling model for West Africa. Agric J 2:577–582

Adel MM (2002) Man-made climatic changes in the Ganges basin. Int J Climatol 22:993–1016

Ainsworth EA, Ort DR (2010) How do we improve crop production in a warming world? Plant Physiol 154(2):526–530

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res Atmos 111:D05109

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: The 2012 revision

Ali MO (2004) More grain from less rain: seed priming—a key technology of lentil production for resource-poor farmers in dry areas. In: Proceedings of the 7th international symposium on water, arsenic and environmental crisis in Bengal Basin issues, impacts and strategies, held in Dhaka, Bangladesh on December 19–20

Ali MH, Talukder MSU (2008) Increasing water productivity in crop production—a synthesis. Agric Water Manag 95(11):1201–1213

Allen JC, Komar PD (2006) Climate controls on US west coast erosion processes. J Coast Res 22 (3):11–529

Allen RJ, Pruitt WO (1986) Rational use of FAO Blaney-criddle formula. J Irrig Drain Eng 112 (2):139–155

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements. FAO irrigation and drainage paper no. 56. FAO, Rome

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg ET, Gonzalez P (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259 (4):660–684

Amarasinghe UA, Sharma BR (2008) Strategic analyses of the national river linking project (NRLP) of India, series 2. In: Proceedings of the workshop on analyses of hydrological, social and ecological issues of the NRLP. International Water Management Institute, Colombo, 500 p

Amthor JS (2001) Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO2 concentration. Field Crop Res 73(1):1–34

ANCID (2000) Open channel seepage and control—literature view of channel seepage identification and measurement, vol 1.1. Australian National Committee on Irrigation and Drainage (ANCID), Victoria

Anonymous (2013). http://abclive.in/india-water-requirement-for-irrigation/

Asokan SM, Dutta D (2008) Analysis of water resources in the Mahanadi River Basin, India under projected climate conditions. Hydrol Process 22(3):589–603. https://doi.org/10.1002/hyp.6962

Awasthi UD, Singh RB, Dubey SD (2007) Effect of sowing date and moisture conservation practice on growth and yield of Indian mustard (*Brassica juncea*) varieties. Indian J Agron 52 (2):151–153

Badenhorst JW, De Lange M, Mokwena ME, Rutherford RJ (2002) Water conservation and water demand management in agriculture: development of water management plans by irrigation water suppliers in South Africa. In: ICID eighteenth congress best paper for 6th Hassan Ismail Award paper, Montreal

Bahu RR, Rajput TBS, Bhattacharya AK, Mishra P (2005) Modelling of water front advance under surge furrow irrigation. J Agric Eng 42(3):68–73

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (2008) Climate change and water. Technical paper of the intergovernmental panel on climate change. IPCC, Secretariat, Geneva, 210 pp

Behera UK, Ruwali KN, Verma PK, Pandey HN (2002) Productivity and water use efficiency of macaroni (*Triticum durum*) and bread wheat (*Triticum aestivum*) under varying irrigation levels and schedules in the vertisols of Central India. Indian J Agron 47(4):518–525

Betts RA, Collins M, Hemming DL, Jones CD, Lowe JA, Sanderson MG (2011) When could global warming reach 4 C? Philosophical transactions of the Royal Society A: mathematical. Phys Eng Sci 369(1934):67–84

Bhan S (1997) Soil and water conservation practical for sustainable agriculture in rainfed areas with particular reference to northern alluvial plains zone of India. Bhagirath XXXXV:55–65

Bharati V, Nandan R, Kumar V, Pandey IB (2007) Effect of irrigation levels on yield, water use efficiency and economics of winter maize (*Zea mays*)-based intercropping systems. Indian J Agron 52(1):27–30

Bouman B (2009) How much water does rice use. Management 69:115–133

Bravo O, Silenzi JC (2002) Strip cropping in the semi-arid region of Argentina: control of wind erosion and soil water accumulation. Soil Sci 167(5):346–352

Burek P, Satoh Y, Fischer G, Kahil MT, Scherzer A, Tramberend S, Hanasaki N (2016) Water futures and solution-fast track initiative (final report). IIASA working paper. IIASA, Laxenburg, p WP-16-006

Burt CM, CLemmens AJ, Strelkoff TS, Solomon KH, Bliesner RD, Hardy LA, Howell TA, Eisenhauer DE (1997) Irrigation performance measures: efficiency and uniformity. J Irrig Drain Eng 123(6):423–442

Busari MA, Kukal SS, Kaur A, Bhatt R, Dulazi AA (2015) Conservation tillage impacts on soil, crop and the environment. Int Soil Water Conserv Res 3(2):119–129

Cardenas LB, Dukes MD (2012) Soil moisture sensor landscape irrigation controllers: a review of multi-study results and future implications. Am Soc Agric Biol Eng 55(2):581–590

Carter RC (2007) Climate, population and groundwater in Africa. In: International conference on groundwater and climate in Africa, held at Kampala, Uganda, during 24–28 June 2008

Carter TR, Hulme M, Viner D (1999) Representing uncertainty in climate change scenarios and impact studies. In: Proceedings of the ECLAT-2 Helsinki workshop, vol 1416. Climatic Research Unit, Norwich

CGWB (2017) Central Ground Water Board. (2014). Dynamic groundwater resources of India. Ministry of Water Resources. http://cgwb.gov.in/GW-Assessment/GWRA-2017-National-Compilation.pdf

Chahal GBS, Sood A, Jalota SK, Choudhury BU, Sharma PK (2007) Yield, evapotranspiration and water productivity of rice-wheat system in Punjab (India) as influenced by transplanting date of rice and weather parameters. Agric Water Manag 88:14–22

Chand M, Bhan S (2002) Root development, water use and water use efficiency of sorghum (*Sorghum bicolor*) as influenced by vegetative barriers in alley cropping system under rainfed conditions. Indian J Agron 47(3):333–339

Chatterjee SK, Banerjee S, Bose M (2012) Climate change impact on crop water requirement in Ganga river basin, West Bengal, India. In: 2012 3rd international conference on biology, environment and chemistry, vol 46. IACSIT Press, Singapore, p 4

Chen C, Wang E, Yu Q (2010a) Modeling wheat and maize productivity as affected by climate variation and irrigation supply in North China Plain. Agron J 102(3):1037–1049

Chen C, Wang E, Yu Q (2010b) Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. Agric Water Manag 97 (8):1175–1184

CWC (1988) Central water commission-water resources of India. CWC publication 30:88

CWC (1993) Central water commission-reassessment of water resources potential of India. Ministry of Water Resources, Government of India. http://cwc.gov.in/sites/default/files/1993-reassessment-waterresourcespotential.pdf

CWC (Central Water Commission) (2014) Guidelines for improving water use efficiency in irrigation, domestic and industrial sectors. Performance Overview and Management

Improvement Organization, Central Water Commission, Govt. of India, RK Puram, Sewa Bhawan, New Delhi-110066

CWC (2015) Central Water Commission, Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, GOI. Water and related statistics (2015). http://www.cwc.nic.in

CWC (2016–17) Central Water Commission annual report 2016–17, Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, GOI. http://www.cwc.gov.in/sites/default/files/CWC_AY_2016-17.pdf. Accessed 15 Apr 2020

CWC (2019a) Central Water Commission-reassessment of water availability in India using space inputs. p 71. http://cwc.gov.in/sites/default/files/main-report.pdf

CWC (2019b) Central Water Commission-water and related statistics 2019. http://cwc.gov.in/sites/default/files/water-and-related-statistics-2019.pdf

CWC (2020) Central Water Commission, Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, GOI. Live storage status of 120 reservoirs of the country as on 16.01.2020. http://cwc.gov.in/sites/default/files/16.01.2020-fb-pdf.pdf

Daccache A, Knox JW, Weatherhead EK, Daneshkhah A, Hess TM (2015) Implementing precision irrigation in a humid climate: recent experiences and on-going challenges. Agric Water Manag 147:135–143. https://doi.org/10.1016/j.agwat.2014.05.018

Dahiya S, Kumar S, Kumar S, Khedwal RS, Harender, Chaudhary C, Ankush (2008) Management practices for improving water use efficiency of crops for boosting crop production. In: Rao RK, Sharma PK, Raghuraman M, Singh JK (eds) Agricultural, allied sciences & biotechnology for sustainability of agriculture, nutrition & food security. Mahima Research Foundation and Social Welfare, Banaras Hindu University, Varanasi, pp 115–121

Dahiya S, Kumar S, Khedwal RS, Jakhar RS (2017) Allelopathy for sustainable weed management. J Pharm Phytochem SP1:832–837

Dahiya S, Kumar S, Kumar S, Khedwal RS, Harender, Chaudhary C, Ankush (2018) Management practices for improving water use efficiency of crops for boosting crop production. In: Rao RK, Sharma PK, Raghuraman M, Singh JK (eds) Agricultural, allied sciences & biotechnology for sustainability of agriculture, nutrition & food security. Mahima Publications, Varanasi, pp 115–121

Das TK, Bandyopadhyay KK, Bhattacharyya R, Sudhishri S, Sharma AR, Behera UK, Saharawat YS, Sahoo PK, Pathak H, Vyas AK, Bhar LM (2016) Effects of conservation agriculture on crop productivity and water-use efficiency under an irrigated pigeon pea–wheat cropping system in the western Indo-Gangetic Plains. J Agric Sci 154(8):1327–1342

Datta PS (2019) Water harvesting for groundwater management: issues, perspectives, scope, and challenges. Wiley. https://www.wiley.com/en-in/Water+Harvesting+for+Groundwater+Management:+Issues,+Perspectives,+Scope,+and+Challenges-p-9781119471905

Davies WJ, Zhang J (1991) Root signals and the regulation of growth and development of plants in drying soil. Ann Rev Plant Physiol Plant Mol Biol 42:55–76

Dehadrai PV (2003) Irrigation in India. FAO Fish Tech Pap 430:59–69. http://www.fao.org/3/y5082e08.htm#bm08

DES, MOA, FW (2014–15) Directorate of Economics and Statistics, Ministry of Agriculture and Farmers' Welfare (2014–15). http://mospi.nic.in/statistical-year-book-india/2018/181

Dhawan V (2017) Water and agriculture in India: background paper for the South Asia expert panel during the global forum for food and agriculture (GFFA). Ostasiatischer Verein e.V, Hamburg

Dhindwal AS, Hooda IS, Malik RK, Kumar S (2006) Water productivity of furrow-irrigated rainy-season pulses planted on raised beds. Indian J Agron 51(1):49–53

Doll P, Siebert S (2001) Global modeling of irrigation water requirement. University of Kassel, Kassel

Dubois O (2011) The state of the world's land and water resources for food and agriculture: managing systems at risk. Earthscan, London

Dukes DM, Zotarelli L, Morgan TK (2010) Use of irrigation technologies for vegetable crops in Florida. HortTechnol 20(1):133–142

DWR, RD, GR (2020) Department of water resources, river development and Ganga rejuvenation, GOI. http://www.cwc.gov.in/water-info#top. Accessed 22 Jan 2020

Eba AT (2018) The impact of alternate furrow irrigation on water productivity and yield of potato at small scale irrigation, Ejere District, West Shoa, Ethiopia. J Plant Sci Agric Res 2(2):16

Einsenhaver DE, Youth CD (1992) Managing furrow irrigation system. In: Proc. Central Plain Irrigation. USA grim, Nebraska, Feb. 5–6

Eitzinger J, Zalud Z, Alexandrov V, Van Diepen CA, Trnka M, Dubrovsky M, Semeradova D, Oberforster M (2001) A local simulation study on the impact of climate change on winter wheat production in North-Eastern Austria. Bodenkultur 52(4):279–292

El Awady MN, El Tantawy MT, Hassan SS, El Ashhab AOM (2003) Water-flow uniformity through irrigation gated-pipes. In: International workshop on improved irrigation technologies and methods: research, development and testing. ICID, New Delhi, pp 18–19

Evett SR, Howell TA, Schneider AD, Wanura DF, Upchurch DR (2001) Water use efficiency regulated by automatic drip irrigation control. In: Proceedings. International irrigation show, San Antonio, TX. The Irrigation Association, Falls Church, pp 49–56

Fahong W, Xuqing SWK (2004) Comparison of conventional, flood irrigated, flat planting with furrow irrigated, raised bed planting for winter wheat in China. Field Crop Res 87(1):35–42

FAO (2017) Water for sustainable food and agriculture a report produced for the G20 presidency of Germany. http://www.fao.org/3/a-i7959e.pdf

Firouzabadi GA (2012) Technical evaluation of low pressure irrigation pipe (Hydroflume) and comparison with traditional and sprinkler irrigation systems. Intl J Agri Crop Sci 4(3):108–113

Fischer G, Tubiello FN, Van Velthuizen H, Wiberg DA (2007) Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080. Technol Forecast Soc Chang 74(7):1083–1107

Flores CI, Holzapfel EA, Lagos O (2010) A dynamic decision support system for farm water management in surface irrigation: model development and application. Chil J Agric Res 70:278–286

Francesca V, Osvaldo F, Stefano P, Paola RP (2010) Soil moisture measurements: comparison of instrumentation performances. J Irrig Drain Eng 136:81–89

Fu B, Wang J, Chen L, Qiu Y (2003) The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. Catena 54(1–2):197–213

Gandhi VP, Namboodiri NV (2009) Groundwater irrigation in India: gains, costs, and risks. Indian Institute of Management Ahmadabad, Research and Publications, Ahmadabad, p 2

Gautam M, Singh AK (2015) Impact of climate change on water resources. In: Climate change Modelling, planning and policy for agriculture. Springer, New Delhi, pp 219–231

Ghadage HL, Pawar VS, Gaikward CB (2005) Influence of planting patterns, irrigation techniques and mulches on growth, yield, water use and economics of cotton (*Gossypium hirsutum*) under irrigated conditions of Western Maharashtra. Indian J Agron 50(2):159–161

Gill BS, Jalota SK (1996) Evaporation from soil in relation to residue rate, mixing depth, soil texture and evaporativity. Soil Technol 8:293–301

Gill MS, Kumar P, Kumar A (2006) Growth and yield of direct seeded rice (*Oryza sativa*) as influenced by seeding technique and seed rate under irrigated conditions. Indian J Agron 51 (4):283–287

Gleick PH (2002) Soft water paths. Nature 418:373

Gleick PH, Pacific Institute for Studies in Development, Environment, and Security, Stockholm Environment Institute (1993) Water in crisis. Oxford Univ. Press, New York, 473 p

Golzardi F, Baghdadi A, Afshar RK (2017) Alternate furrow irrigation affects yield and water-use efficiency of maize under deficit irrigation. Crop Pasture Sci 68(8):726–734

Gonzalez Perea R, Daccache A, Rodriguez Diaz JA, Poyato CE, Knox JW (2018) Modelling impacts of precision irrigation on crop yield and in-field water management. Prec Agric 19:497–512. https://doi.org/10.1007/s11119-017-9535-4

Goswami VK, Kaushik SK, Gautam RC (2002) Effect of intercropping and weed control on nutrient uptake and water use efficiency of pearl millet (*Pennisetum glaucum*) under rain fed conditions. Indian J Agron 47(4):504–508

Goumopoulos C, O'Flynn B, Kameas A (2014) Automated zone-specific irrigation with wireless sensor/actuator network and adaptable decision support. Comput Electron Agric 105:20–33

Govindarajan S, Ambujam NK, Karunakaran K (2008) Estimation of paddy water productivity (WP) using hydrological model: an experimental study. Paddy Water Environ 6(3):327–339

Goyal MR, Chavan VK, Tripathi VK (eds) (2016) Innovations in micro irrigation technology. CRC Press, New York

Guhathakurta P, Sreejith OP, Menon PA (2011) Impact of climate change on extreme rainfall events and flood risk in India. J Earth Syst Sci 120:359–373. https://link.springer.com/article/10.1007/s12040-011-0082-5

Gupta US (ed) (1975) Physiological aspects of dryland farming. Oxford and IBH Publishing, New Delhi

Gupta SK, Deshpande RD (2004) Water for India in 2050: first-order assessment of available options. Curr Sci 86:1216–1224

Gupta A, Kumar A (2018) Climate resilient agro-technologies for enhanced crop and water productivity under water deficit agro-ecologies. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 339–356

Gupta RK, Naresh RK, Hobbs PR, Ladha JK (2002) Adopting conservation agriculture in the rice–wheat system of the Indo-Gangetic Plains: new opportunities for saving water. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP, Ladha JK (eds) Water wise rice production. Proceedings of the international workshop on water wise rice production, April 8–11, 2002, Los Banos, Philippines. International Rice Research Institute, Los Banos, pp 207–222

Hedley CB, Yule IJ, Tuohy MP, Vogeler I (2009) Key performance indicators for simulated variable-rate irrigation of variable soils in humid regions. Trans ASABE 52(5):1575–1584. https://doi.org/10.13031/2013.29146

Hillel D (1997) Improving water use efficiency. Small-scale irrigation for arid zones: principles and options. Natural Resources Management and Environment Department, FAO, New York, pp 13–18

Hipsey M, Arheimer B (2013) Challenges for water-quality research in the new IAHS decade on: hydrology under societal and environmental change. In: Understanding freshwater quality problems in a changing world. IAHS Press, Wallingford, pp 17–29

Hira GS (2004) Status of water resources in Punjab and management strategies. Workshop papers of groundwater use in NW India, held at New Delhi. Centre for Advancement of Sustainable Agriculture, New Delhi, 65 pp

Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H, Kanae S (2013) Global flood risk under climate change. Nat Clim Chang 3:816–821. https://www.nature.com/articles/nclimate1911

Horst MG, Shamutalov SS, Goncalves JM, Pereira LS (2007) Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. Agric. Water Manage 87:115–127

Huang Y, Wang H, Xiao W, Chen LH, Yan DH, Zhou YY, Jiang DC, Yang MZ (2018) Spatial and temporal variability in the precipitation concentration in the upper reaches of the Hongshui river basin, southwestern China. Adv Meteorol 2018:4329757

IAEA-International Atomic Energy Agency Bulletin 53-1 (2011) All about water. https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull53-1/53105911720.pdf

IMD (2019) Ministry of Earth Sciences, India Meteorological Department. https://data.gov.in/catalog/all-india-area-weighted-monthly-seasonal-and-annual-rainfall-mm?filters%5Bfield_catalog_reference%5D=85825&format=json&offset=0&limit=6&sort%5Bcreated%5D=desc. Accessed 22 Jan 2020

Indian National Committee on Irrigation and Drainage (1994) Drip irrigation in India. New Delhi

Indian Standards Measurement (1980) Measurement of seepage losses from canals. IS: 9452 (part I and II). Indian standard code of practice. Indian Bureau of Standard, New Delhi

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change. Cambridge University Press, Cambridge/New York. www.ipcc.ch/pdf/special-reports/srex/SREX_Full_Report.pdf

IPCC (2013) Summary for policymakers. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013 the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

IPCC (2014) Synthesis report, contribution of working groups I, II and III to the final assessment report of the intergovernmental panel on climate change, 2014. IPCC, Geneva

Jain SK, Agarwal PK, Singh VP (2007) Hydrology and water resources of India, vol 57. Springer, Dordrecht. https://www.springer.com/gp/book/9781402051791

Jangir CK, Singh D, Kumar S (2016) Yield and economic response of biofertilizer and fertility levels on black gram (Vigna mungo L.). Prog Res Int J 11(Special-VIII):5252–5254

Jat ML, Gautam RC (2001) Productivity and water use of rain fed pearl millet (Pennisetum glaucum) as influenced by summer ploughing and *in-situ* moisture conservation practices under semiarid conditions of north-West India. Indian J Agron 46(2):266–272

Jat ML, Singh S, Rai HK, Chhokar RS, Sharma SK, Gupta RK (2005) Furrow irrigated raised bed (FIRB) planting technique for diversification of rice-wheat system in indo-Gangetic Plains. Jpn Assoc Int Collab Agric For 28(1):25–42

Jat ML, Gathala MK, Saharawat YS, Tetarwal JP, Gupta R (2013) Double no-till and permanent raised beds in maize–wheat rotation of north-western Indo-Gangetic plains of India: effects on crop yields, water productivity, profitability and soil physical properties. Field Crop Res 149:291–299

Jin K, Cai DX, Lv JJ, Wu HJ, Long XN (2006) Effects of tillage practices on erosion and winter wheat yield on sloping dryland. J Soil Water Conserv 20:1–6

John WH, Nicholas JC, Evan WC, Thomas MS, Bill W (2009) IrriSatSMS irrigation water management by satellite and SMS - a utilization framework. CSIRO Land and Water Science, Toowoomba

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017a) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in Indo-Gangatic Plains of India. J Curr Microb Appl Sci 6(3):152–163

Kakraliya SK, Kumar N, Dahiya S, Kumar S, Yadav DD, Singh M (2017b) Effect of integrated nutrient management on growth dynamics and productivity trend of wheat (Triticum aestivum L.) under irrigated cropping system. J Plant Dev Sci 9(1):11–15

Kang S, Liang Z, Pan Y, Shi P, Zhang J (2000) Alternate furrow irrigation for maize production in an arid area. Agric Water Manag 45(3):267–274

Kaur R (2006) Response of zero-till and bed planted wheat (*Triticum aestivum L.*) to varying irrigation schedules. M.Sc. thesis, Punjab Agricultural University, Ludhiana

Kharin VV, Zwiers FW, Zhang X, Wehner M (2013) Changes in temperature and precipitation extremes in the CMIP5 ensemble. Clim Chang 119(2):345–357

Kijne JW, Barker R, Molden D (eds) (2003) Water productivity in agriculture: limits and opportunities for improvement, vol 1. CABI, Wallingford

Kim Y, Evans RG (2009) Software design for wireless sensor-based site-specific irrigation. Comput Electron Agric 66:159–165

Kisekka I, Aguilar J, Lamm F, Rogers D (2014) Using soil water and canopy temperature to improve irrigation scheduling for corn. In: Proceeding for the 2014 irrigation association conference, Phoenix, Arizona. Irrigation Association, Falls Church

Kort J (1988) Benefits of windbreaks to field and forage crops. Agric Ecosyst Environ 22:165–190

Kramer PJ (1969) Plant and soil water relationship. A modern synthesis. M’cGrow Hill, New York

Kumar A, Rana KS (2007) Performance of pigeon pea (*Cajanus cajan*) + green gram (*Phaseolus radiates*) intercropping system as influenced by moisture conservation practice and fertility level under rainfed conditions. Ind J Agron 52(1):31–35

Kumar MD, van Dam JC (2009) Improving water productivity in agriculture in India: Beyond 'More Crop per Drop'. No. 612–2016-40570

Kumar M, Singh H, Hooda RS, Khippal A, Singh T (2003) Grain yield, water use and water use efficiency of pearl millet (*Pennisetum glaucum*) hybrids under variable nitrogen application. Indian J Agron 48(1):53–55

Kumar A, Sharma KD, Yadav A (2010) Enhancing yield and water productivity of wheat (*Triticum aestivum*) through furrow irrigated raised bed system in the indo-Gangetic Plains of India. Indian J Agric Sci 80(3):198–202

Kumar J, Patel N, Rajput TBS, Kumar M (2016a) Sensor network based irrigation system for real time irrigation scheduling in vegetable crops under different methods of irrigation. Indian J Agric Sci 86(11):1433–1437

Kumar J, Patel N, Rajput TBS (2016b) Development and integration of soil moisture sensor with drip system for precise irrigation scheduling through mobile phone. J Appl Nat Sci 8 (4):1959–1965

Kumar J, Patel N, Rajput TBS (2017a) Development of decision support system based on crop water demand and soil moisture deficit for real time irrigation scheduling. Indian J Agric Sci 87 (5):648–652

Kumar S, Singh MK, Meena RS, Hingonia K (2017b) Influence of crop geometry and cultivars on growth, yield and production efficiency of dry direct-seeded rice (*Oryza sativa* L.). J Appl Nat Sci 9(4):2469–2476

Kumar S, Karaliya SK, Chaudhary S (2017c) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. J Curr Microb Appl Sci 6 (3):142–151

Kumar S, Meena RS, Jakhar SR, Jangir CK, Gupta A, Meena BL (2019) Adaptation strategies for enhancing agricultural and environmental sustainability under current climate. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 226–274

Lal R (2005) Climate change, soil carbon dynamics, and global food security. Routledge in Association with GSE Research, Abingdon, pp 113–143

Layek J, Das A, Mitran T, Nath C, Meena RS, Yadav GS, Shivakumar BG, Kumar S, Lal R (2018) Cereal+legume intercropping: An option for improving productivity and sustaining soil health. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 347–386. https://doi.org/10.1007/978-981-13-0253-4_11

Leib BG, Hattendorf M, Elliott T, Mattews G (2002) Adoption and adaptation of scientific irrigation scheduling: trends from Washington, USA as of 1998. Agric Water Manag 55:105–120

Leib B, Jabro J, Matthews G (2003) Field evaluation and performance comparison of soil moisture sensors. Soil Sci 168:396–408

Li FM, Liu XR, Wang J (2001) Effects of pre-sowing irrigation and P fertilization on spring wheat yield information. Acta Ecol Sin 21:1941–1946

Liang YL (1996) The adjustment of soil water and nitrogen phosphorus nutrition on root system growth of wheat and water use. Acta Ecol Sin 16:258–264

Liang ZS, Zhang FS, Zhang JH (2002) The relations of stomatal conductance, water consumption, growth rate to leaf water potential during soil drying and rewatering cycle of wheat. Bot Bull Acad Sin 43:187–192

Luo Y, Wang Z, Liu X, Zhang M (2014) Spatial and temporal variability of precipitation in Haihe River Basin, China: characterization and management implications. Adv Meteorol 2014:143246

Maheswari M, Sarkar B, Vanaja M, Srinivasa Rao M, Prasad JVNS, Prabhakar M, Ravindra Chary G, Venkateswarlu B, Ray Choudhury P, Yadava DK, Bhaskar S, Alagusundaram K (eds) (2019) Climate resilient crop varieties for sustainable food production under aberrant weather conditions. ICAR-Central Research Institute for Dryland Agriculture, Hyderabad, p 64

Mahey RK, Kaur M, Vashist KK, Mahal SS, Deol KS, Sidhu AS (2008) Effect of planting techniques and seed rate on soybean (*Glycine max L. Merril*) and irrigation water saving. Indian J Ecol 35(2):159–161

Mazdiyasni O, AghaKouchak A (2015) Substantial increase in concurrent droughts and heatwaves in the United States. Proc Natl Acad Sci 112(3):11484–11489. https://doi.org/10.1073/pnas.1422945112

McClymont D (2007) Development of a decision support system for furrow and border irrigation. Ph.D. thesis, University of Southern Queensland, Australia

McCready MS, Dukes MD, Miller GL (2009) Water conservation potential of intelligent irrigation controllers on St. Augustine grass. Agric Water Manag 96:1623–1632

McMahon TA, Peel MC, Lowe L, Srikanthan R, McVicar TR (2013) Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. Hydrol. Earth Syst Sci 17:1331–1363

Meehl GA, Washington WM, Collins WD, Arblaster JM, Hu A, Buja LE, Strand WG, Teng H (2005) How much more global warming and sea level rise? Science 307(5716):1769–1772

Meena H, Meena RS, Lal R, Yadav GS, Mitran T, Layek J, Patil SB, Kumar S, Verma T (2017) Response of sowing dates and bio regulators on yield of clusterbean under current climate in alley cropping system in eastern U.P., India. Legume Res 41(4):563–571. https://doi.org/10.18805/LR-3759

Meena RS, Kumar V, Yadav GS, Mitran T (2018a) Response and interaction of *Bradyrhizobium japonicum* and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Mitran T, Kumar S, Yadav GS, Bohra JS, Datta R (2018b) Application of remote sensing for sustainable agriculture and forest management. Inform Proc Agric 5:295–297. https://doi.org/10.1016/j.inpa.2018.03.003

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Mehla RS, Verma JK, Gupta RK, Hobbs PR (2000) Stagnation in the productivity of wheat in the Indo-Gangetic Plains: zero-till-seed-cum-fertilizer drill as an integrated solution. Rice–wheat consortium paper series 8. RWC, New Delhi

Meti CB (2012) Studies on factors influencing the drip irrigation adoption, constraints and remedial measures to increase area under drip irrigation. Int J Agric Eng 5:236–239

Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. Nature 438:347–350. https://doi.org/10.1038/nature04312

Milne GA, Gehrels WR, Hughes CW, Tamisiea ME (2009) Identifying the causes of sea-level change. Nat Geosci 2(7):471–478

Mintesinot B, Verplancke H, Ranst EV, Mitiku H (2007) Enhancing the productivity of irrigated Vertisols: a comparative study between a traditional method and surge/ intermittent management. Soil Use Manag 23:36–39

Mishra V, Tiwari AD, Aadhar S, Shah R, Xiao M, Pai DS, Lettenmaier D (2019) Drought and famine in India, 1870–2016. Geophys Res Lett 46(4):2075–2083

MoEF (2004) India's initial national communication to United Nations framework convention on climate change. Ministry of Environment and Forests, GOI, New Delhi, pp 72–82

MoEF (2012) Indian second national communication to the United Nations framework convention on climate change. Ministry of Environment and Forests, GOI, New Delhi

Mohan S, Ramsundram N (2014) Climate change and its impact on irrigation water requirements on temporal scale. Irrig Drain Syst Eng 3(1):1–8

Molden D, Murray Rust H, Sakthivadivel R, Makin I (2003) A water-productivity framework for understanding and action. In: Kijne JW, Barker R, Molden D (eds) Water productivity in agriculture: limits and opportunities for improvement. CABI Publishing and International Water Management Institute, Wallingford/Colombo

Mondal A, Mujumdar PP (2015) Modelling non-stationarity in intensity, duration and frequency of extreme rainfall over India. J Hydrol 521:217–231

MOSPI (2018–19) Ministry of Statistics and Programme Implementation. http://mospi.nic.in/sites/default/files/press_release/Presss%20note%20for%20first%20advance%20estimates%202018-19.pdf

MOSPI (2019) Ministry of Statistics and Program Implementation, statistical year book India 2018. http://mospi.nic.in/statistical-year-book-india/2018/177

Mujumdar PP (2008) Implications of climate change for sustainable water resources management in India. Phys Chem Earth Parts A/B/C 33(5):354–358

Nadeem MA, Tanveer A, Ayub AAM, Tahir M (2007) Effect of weed control practice and irrigation levels on weeds and yield of wheat (*Triticum aestivum*). Indian J Agron 52(1):60–63

Nalayini P, Raja R, Kumar AA (2006) Evapotranspiration based scheduling of irrigation through drip for cotton (*Gossypium hirsutum*). Indian J Agron 51(3):232–235

Nejadhashemi AP, Wardynski BJ, Munoz JD (2012) Large-scale hydrologic modelling of the Michigan and Wisconsin agricultural regions to study impacts of land use changes. Trans ASABE 55(3):821–838

NMSA (2012) National Mission on Sustainable Agriculture, Department of Agriculture, Cooperation & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India. https://nmsa.dac.gov.in/

NWM (2011) National Water Mission, Ministry of Jal Shakti, Department of Water resources, RD & GR. Govt. of India. http://nwm.gov.in/?q=schemes

O'Gorman PA (2015) Precipitation extremes under climate change. Curr Clim Change Rep 1 (2):49–59. https://doi.org/10.1007/s40641-015-0009-3

OECD (2014). https://www.oecd.org/policy-briefs/India-Improving-Water-Security.pdf

Ogbuehi SN, Brandle JR (1981) Influence of windbreak-shelter on soybean production under rainfed conditions. Agron J 73(4):625–628

OGD - Open Government Data Platform (2018) Government of India. https://data.gov.in/resources/river-basin-wise-water-resources-potential-river-basins-india-reply-unstarred-question-26

Orlowsky B, Seneviratne SI (2012) Global changes in extreme events: regional and seasonal dimension. Clim Chang 110(3–4):669–696

Pal SK, Thakur R, Verma UN, Singh MK (1996) Water requirement of wheat as influenced by irrigation water, seeding date and fertilizer. Indian J Agric Sci 66(3):177–179

Panda BB, Bandyopadhyay SK, Shivay YS (2004) Effect of irrigation level, sowing dates and varieties on growth, yield attributes, yield, consumptive water use and water use efficiency of Indian mustard (*Brassica juncea*). Indian J Agric Sci 74(6):331–342

Pandey SK, Kaushik SK, Gautam RC (1988) Response of rainfed pearlmillet (*Pennisetum glaucum*) to plant density and moisture conservation. Indian J Agri Sci 58(7):517–520

Parameswaran G, Sivaprasath K (2016) Arduino based smart drip irrigation system using internet of things. Int J Eng Sci Comput 6:5518–5521

Parekh F, Prajapati KP (2013) Climate change impacts on crop water requirement for Sukhi reservoir project. Int J Innov Res Sci Eng Technol 2(9):2–10

Parihar SS (2004) Effect of crop establishment method, tillage, irrigation and nitrogen on production potential of rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system. Indian J Agron 49(1):1–5

Passioura J (2006) Increasing crop productivity when water is scarce-from breeding to field management. Agric Water Manag 80:176–196

Pathak H, Pramanik P, Khanna M, Kumar A (2014) Climate change and water availability in Indian agriculture: impacts and adaptation. Indian J Agric Sci 84:671–679

Pawar J, Khanna R (2018) More crop per drop: ways to increase water use efficiency for crop production: a review. Int J Chem Stud 6(3):3573–3578

Petr T (ed) (2003) Fisheries in irrigation systems of arid Asia, vol 430. Food & Agriculture Organisation, Rome. http://www.fao.org/3/y5082e00.htm

PIB (2018) Press Information Bureau, Ministry of Finance, Government of India. https://pib.gov.in/newsite/PrintRelease.aspx?relid=186413

PIB (2019a) Press Information Bureau. Ministry of Jal Shakti, Government of India. https://pib.gov.in/newsite/PrintRelease.aspx?relid=195633. Accessed 09 Dec 2019

PIB (2019b) Press Information Bureau. http://pib.nic.in/website/PrintRelease.aspx

PMKYS (2015). https://pmksy.gov.in/microirrigation/Archive/August2015.pdf

PMKYS (2020) Pradhan Mantri Krishi Sinchayee Yojana, Ministry of Agriculture & Farmers Welfare, Govt. of India. http://pmksy.gov.in/. Accessed 15 Apr 2020

Prabhata KS, Govinda CM, Bhagu RC (2001) Design of minimum seepage loss canal sections with drainage layer at shallow depth. J Irrig Drain Eng 127:287–294

Pramanik SC, Singh NB, Singh KK (2009) Yield, economics and water use efficiency of chickpea (*Cicer arietinum*) under various irrigation regimes on raised bed planting system. Indian J Agron 54(3):315–318

Prihar SS, Jalota SK, Steiner JL (1996) Residue management for reducing evaporation in relation to soil type and evaporativity. Soil Use Manag 12:150–157

Priyan K (2015) Spatial and temporal variability of rainfall in Anand District of Gujarat state. Aquat Procedia 4:713–720

Priyan K, Panchsal R (2017) Micro-irrigation: An efficient technology for India's sustainable agricultural growth. Kalpa Publ Civ Eng 1:398–402

Purcell B (1999) Determining a framework, terms and definitions for water use efficiency in irrigation, Land & Water Resources Research & Development Corporation. http://www.insidecotton.com/xmlui/handle/1/2130

Rahmstorf S (2010) A new view on sea level rise. Nat Clim Chang 1(1004):44–45

Rajput TBS, Patel N (2003) User's guide for – DRIPD- software for designing drip irrigation system. TB-ICN: 2003. WTC, IARI, New Delhi

Rani A, Bandyopadhyay KK, Krishnan P, Sarangi A, Datta SP (2019) Effect of tillage, residue and nitrogen management on soil water dynamics and water productivity of wheat in an Inceptisol. J Indian Soc Soil Sci 67(1):44–54

Rao SC, Phillips WA (1993) Effect of seed priming and soil residue on seedling emergence and forage production of brassicas. J Sustain Agric 3(2):89–98

Rashid A, Haris D, Hollington PA, Khattak RA, Ahmad R, Malik KA (2002) On-farm seed priming: a key technology for improving the livelihood of resource-poor farmers of saline lands. Prospect Saline Agric 37:423–431

Rashidi M, Abbasi S, Gholami M (2009) Interactive effect of plastic mulch and tillage methods on yield and yield components of tomato. Am-Eurasian J Agric Environ Sci 5(3):420–427

Rathore BS, Rana VS, Nanwal RK (2008) Effect of plant density and fertilizer levels on growth and yield of pearl millet (*Pennisetum glaucum*) hybrids under limited irrigation conditions in semi-arid environment. Indian J Agri Sci 78(8):667–670

Rawal S (2017) IOT based smart irrigation system. Int J Comput Appl 159(8):7–11

Reddy VR, Reddy PP, Reddy MS, Raju SR (2005) Water use efficiency: a study of system of rice intensification (SRI) adoption in Andhra Pradesh. Indian J Agric Econ 60(3):15

Reddy M, Malla PB, Rao LJ (2008) Response of *rabi* pigeon pea to irrigation scheduling and weed management in. Alfisols J Food Legumes 21(4):237–239

Rehana S, Mujumdar PP (2013) Regional impacts of climate change on irrigation water demands. Hydrol Process 27:2918–2933. https://doi.org/10.1002/hyp.9379

Richey AS, Thomas BF, Lo MH, Reager JT, Famiglietti JS, Voss K, Rodell M (2015) Quantifying renewable groundwater stress with GRACE. Water Resour Res 51(7):5217–5238

Rosegrant MW, Ringler C, Zhu T (2009) Water for agriculture: maintaining food security under growing scarcity. Annu Rev Environ Resour 34:205–222

Saha B (2015) A critical study of water loss in canals and its reduction measures. Int J Eng Res Appl 5(3):53–56

Sandhu BS, Khera KL, Prihar SS, Singh B (1980) Irrigation needs and yield of rice on a sandy-loam soil as affected by continuous and intermittent submergence. Ind J Agric Sci 50(6):492–496

Sani BM, Danmowa NM, Sani YA, Jaliya MM (2011) Growth, yield and water use efficiency of maize-sorghum intercrop at Samaru, Northern Guinea Savannah, Nigeria. Niger J Basic Appl Sci 19(2):253–259

Sarkar AA, Hassan AA, Ali MH, Karim NN (2002) Supplemental irrigation for Binashail rice cultivation at two agro-ecological zones of Bangladesh. Bangladesh J Agric Sci 29(1):95–100

Sarma A, Singh H, Nanwal RK (2005) Growth, yield and water use efficiency of wheat (Triticum aestivum) as influenced by integrated nutrient management under adequate and limited irrigation. Haryana J Agron 21(2):96–100

Sauer TJ, Hatfield JL, Prueger JH (1996) Corn residue age and placement effects on evaporation and thermal regime. Soil Sci Soc Am J 60:1558–1564

Shah T (2009) Climate change and groundwater: India’s opportunities for mitigation and adaptation. Environ Res Lett 4:035005

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019) Growth, yield and quality of cluster bean (Cyamopsis tetragonoloba) as influenced by integrated nutrient management under alley cropping system. Indian J Agric Sci 89(11):1876–1880

Shatat M, Worall M, Riffat S (2013) Opportunities for solar water desalination worldwide. Sustain Cities Soc 9:67–80. https://www.sciencedirect.com/science/article/abs/pii/S2210670713000176

Shivani Verma UNL, Sanjeev K, Pal SK, Thakur R (2003) Growth analysis of wheat (Triticum aestivum) cultivars under different seeding dates and irrigation levels in Jharkhand. Indian J Agron 48(4):282–286

Shock CC, Feibert EBG, Saunders LD, Eldredge EP (2002) Automation of subsurface drip irrigation for crop research. In: Proceeding of the world congress of computer in agriculture and natural resources, held during 13–15 March at Iguana Falls, Brazil. ASABE, St. Joseph, pp 809–816

Sihag SK, Singh MK, Meena RS, Naga SR, Bahadur S, Gaurav YRS (2015) Influences of spacing on growth and yield potential of dry direct seeded rice (Oryza sativa L.) cultivars. Ecoscan 9 (1&2):517–519

Singh C, Mahey RK (1998) Response of hybrid sunflower to planting dates, methods of sowing and timing of last irrigation. J Res Punjab Agric Univ 35(1–2):8–11

Singh V, Bhunia SR, Chauhan RPS (2003) Response of late-sown wheat (*Triticum aestivum*) to row spacing-cum-population densities and levels of nitrogen and irrigation in North-Western Rajasthan. Indian J Agron 48(3):178–181

Singh MK, Singh RP, Singh RK (2004) Influence of crop geometry, cultivar and weed-management practice on crop-weed competition in chickpea (*Cicer arietinum*). Indian J Agron 49 (4):258–261

Singh AK, Manibhushan NC, Bharati RC (2008) Suitable crop varieties for limited irrigated conditions in different agro climatic zones of India. Int J Trop Agric 26(3–4):491–496

Singh L, Beg MKA, Akhter S, Qayoom S, Lone BA, Singh P (2014) Efficient techniques to increase water use efficiency under rainfed eco-systems. J AgriSearch 1(4):193–200

Sinha AK (2003) Development of an integrated disaster management system in India: importance of reliable information. In: International conference on total disaster risk management. ADRC, Kobe, pp 2–4

Sirotenko OD, Abashina HV, Pavlova VN (1997) Sensitivity of the Russian agriculture to changes in climate, CO_2 and tropospheric ozone concentrations and soil fertility. Clim Chang 36 (1–2):217–232

Sivanappan RK (1994) Prospects of micro-irrigation in India. Irrig Drain Syst 8(1):49–58

Sivanappan RK (2009) Development of micro-irrigation in India. Lecture note delivered in winter school on micro irrigation, 4–24 March 2009, Water Technology Centre, Indian Agricultural Research Institute, New Delhi, India

Skierucha W, Wilczek A (2010) A FDR sensor for measuring complex soil dielectric permittivity in the 10–500 MHz frequency range. Sensors 10:3314–3329. https://doi.org/10.3390/s100403314

Smith M (1991) CROPWAT: manual and guidelines. FAO of UN, Rome

Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (2013) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, 1535. IPCC, Geneva

Stone JF, Nofziger DL (1993) Water use and yields of cotton grown under wide-spaced furrow irrigation. Agric Water Manag 24(1):27–38

Stone JF, Garton JE, Webb BB, Reeves HE, Keflemariam J (1979) Irrigation water conservation using wide-spaced furrows. Soil Sci Soc Am J 43(2):407–411

Stone JF, Reeves HE, Garton JE (1982) Irrigation water conservation by using wide- spaced furrows. Agric Water Manag 5:309–317

Stringham GE (1988) Surge flow irrigation: final report of the western regional research project W-163. Logan, Utah Agricultural Experiment Station, Utah State University

Subramanian V (2000) Water: quantity-quality perspectives in South Asia. Kingston International Publishers, Surrey, p 256

Tabbal DF, Bhuiyan SI, Sibayan EB (2000) The dry-seedling technique for saving water in irrigated rice production system. In: Pandey S, Mortimer M, Wade L, Tuong TP, Lopez K, Hardy B (eds) Direct seedling: research strategies and opportunities. Proceedings of the workshop, Bankok, Thailand, January 25–28. International Rice Research Institute, Los Baños

Thompson RB, Gallardo M, Valdez LC, Fernández MD (2007) Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors. Agric Water Manag 88(1–3):147–158

Tomaszewska RKM, Arski JZ, Dudek S (2012) Meteorological automated weather station data application for plant water requirements estimation. Comput Electron Agric 88:44–51

Trost B, Prochnow A, Drastig K, Meyer-Aurich A, Ellmer F, Baumecker M (2013) Irrigation, soil organic carbon and N2O emissions: a review. Agron Sustain Dev 33(4):733–749. https://doi.org/10.1007/s13593-013-0134-0

Turner NC (2004) Sustainable production of crops and pastures under drought in a Mediterranean environment. Ann Appl Biol 144:139–147

Uchdadiya KD, Patel JN (2014) Seepage losses through unlined and lined canals. Int J Adv Appl Math Mech 2(2):88–91

UNESCO (2003) Water for people, water for life: The United Nations world water development report: a joint report by the twenty-three UN agencies concerned with freshwater. UNESCO. https://www.un.org/esa/sustdev/publications/WWDR_english_129556e.pdf

Unnikrishnan AS, Shankar D (2007) Are sea levels trends along the North Indian Ocean coasts consistent with global estimates? Glob Planet Change 57:301–307

UN-Water (2018) UN world water development report, nature-based Solutions for water

Urso GD, Michele CD, Bolognesi SF (2013) IRRISAT: the Italian on-line satellite irrigation advisory service. In: EFITA-WCCA-CIGR conference “sustainable agriculture through ICT innovation”, Turin, Italy

USGS-United States Geological Survey (2019) The distribution of water on, in, and above the earth. https://www.usgs.gov/media/images/distribution-water-and-above-earth

Valipour M (2013) Increasing irrigation efficiency by management strategies: cutback and surge irrigation. J Agric Biol Sci 8(1):35–43

Van der Kooij S (2009) Why Yunquera will get drip irrigation. Social groups identity and construction of meanings as an approach to understand technological modernization. M.Sc. thesis research, Wageningen University, Wageningen

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan region, India. Int J Chem Stud 5(4):1558–1560

Vellidis G, Tucker M, Perry C, Kvein C, Bednarz C (2008) A real-time wireless smart sensor array for scheduling irrigation. Comput Electron Agric 61:44–50

Vermeer M, Rahmstorf S (2009) Global Sea level linked to global temperature. Proc Natl Acad Sci 106(51):21527–21532

Vinnarasi R, Dhanya CT (2016) Changing characteristics of extreme wet and dry spells of Indian monsoon rainfall. J Geophys Res Atmos 121(5):2146–2160

Walker B, Holling CS, Carpenter SR, Kinzig A (2004) Resilience, adaptability and transformability in social–ecological systems. Ecol Soc 9(2):5

Wu SY, Yarnal B, Fisher A (2002) Vulnerability of coastal communities to sea-level rise: a case study of Cape May County, New Jersey, USA. Clim Res 22(3):255–270

Xiao G, Zheng F, Qiu Z, Yao Y (2013) Impact of climate change on water use efficiency by wheat, potato and corn in semiarid areas of China. Agric Ecosyst Environ 181:108–114

Xie M, Kuffner U, Le Moigne G (1993) Using water efficiently: technological options. World Bank technical paper number 205. World Bank, Washington, D.C.

Yadav RL, Singh SR, Prasad K, Dwivedi BS, Batta RK, Singh AK (2000) Management of irrigated agro ecosystem. In: Natural resource management for agricultural production in India. Indian Society of Soil Science, New Delhi, pp 775–870

Yang C, Huang G, Chai Q, Luo Z (2011a) Water use and yield of wheat/maize intercropping under alternate irrigation in the oasis field of northwest China. Field Crop Res 124(3):426–432

Yang X, Chen C, Luo Q, Li L, Yu Q (2011b) Climate change effects on wheat yield and water use in oasis cropland. Int J Plant Prod 5(1):84–94

Zhang LX, Li SX (2005) Effects of application of nitrogen, potassium and glycinebetaine on alleviation of water stress in summer maize. Sci Agric Sin 38:1401–1407

Zhang J, Sun J, Duan A, Wang J, Shen X, Liu X (2007) Effects of different planting patterns on water use and yield performance of winter wheat in the Huang-Huai-Hai plain of China. Agric Water Manag 92:41–47

Zhang Y, Ji R, Cai F, Zhang S, Zhao X (2012) Effects of climate change on water use efficiency in rain-fed plants. Int J Plant Prod 6(4):513–534

Zhang J, Ren W, An P, Pan Z, Wang L, Dong Z, He D, Yang J, Pan S, Tian H (2015) Responses of crop water use efficiency to climate change and agronomic measures in the semiarid area of northern China. PLoS One 10(9):e0137409

Zhao L, Wu L, Li Y, Animesh S, Zhu D, Uphoff N (2010) Comparisons of yield, water use efficiency, and soil microbial biomass as affected by the system of rice intensification. Commun Soil Sci Plant Anal 41(1):1–12

Zwart SJ, Bastiaanssen WG (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric Water Manag 69(2):115–133

Fate of Micronutrients in Alkaline Soils

16

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Abstract

Elements essentially required for the proper functioning of plants are termed as “essential nutrients” that are classified into macro (H, O, C, P, K, N, Ca, Mg, S) and micro (B, Fe, Cu, Mn, Zn, Ni, Mo, Cl) nutrients. Micronutrients though required in minute quantity are an integral part of plant nutrition, and their absence from the system significantly affects plant growth and biochemical functioning. Metallic micronutrient availability in soil being dependent upon soil pH and redox potential has become an issue for alkaline soils. In general, all micronutrients are bioavailable in acidic to neutral soil pH except Mo. Thus, making the nonsignificant supply of these nutrients in alkaline soil a constraint for sustainable agriculture. Besides soil chemical properties, soil biota and rhizosphere root chemistry and plant symbiotic associations also affect micronutrient solubilization and uptake by plants. Modification of rhizosphere chemistry, the introduction of mycorrhizal association and biofertilizers can be an option for increasing bioavailability of these nutrients in alkaline soils. Using biofertilizers and screening, enrichment and incorporation of Fe, Zn, Cu, and Mn solubilizing, and S reducing bacteria are only useful if we can sustain proper microbial count per gram of soil. Application of different inorganic and organic amendments, fertigation of synthetic nutrient formulation, and foliar application of micronutrient products are acceptable and economical options for tackling this issue in alkaline soils. This chapter is an effort to summarize all issues associated with the availability of micronutrients in alkaline soils and possible options for enhancement of bioavailable fraction, uptake and assimilation of these nutrients by various crop plants.

Keywords

Alkaline soil · Amendments · Conditioners · Micronutrients · Soil pH

Abbreviations

AM	Arbuscular mycorrhizal
As	Arsenic
ATP	Adenosine triphosphate
B	Boron
C	Carbon
Ca	Calcium
$CaCO_3$	Calcium carbonate
CCE	Calcium carbonate equivalent
CEC	Cation exchange capacity
CES	Cation exchange site
Cl	Chlorine
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate
Cu	Copper
DNA	Deoxyribonucleic acid
EcM	Ectomycorrhizal
Fe	Iron
H	Hydrogen
H^+	Hydrogen ion
HCO_3^-	Bicarbonate
K	Potassium

KSR	Potassium solubilizing rhizobacteria
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
N_2O	Nitrous oxide
NFR	Nitrogen-fixing rhizobacteria
Ni	Nickel
O	Oxygen
OH^-	Hydroxide
OM	Organic matter
P	Phosphorus
PGPR	Plant growth-promoting rhizobacteria
RNA	Ribonucleic acid
S	Sulfur
Si	Silicon
Zn	Zinc
$ZnCl^+$	Zinc chloride ion

16.1 Introduction

Increasing world population coupled with the issue of malnutrition has urged the requirement for suitable and sustainable agricultural practices to get more yield with improved nutritious quality (Masunaga and Marques Fong 2018). Obtaining high yield and the proficient quality of food relies upon the accurate application of micro and macronutrients into the soil (Rutkowska et al. 2014). Essential nutrients are elements involved in plant metabolism; without them, plants cannot complete their life cycle and their deficiency can only be treated with the application of the same nutrient (Fageria et al. 2002). Plants require seventeen nutrients for their development and growth which are carbon (C), hydrogen (H), oxygen (O), potassium (K), nitrogen (N), phosphorus (P), magnesium (Mg), calcium (Ca), boron (B), manganese (Mn), iron (Fe), sulfur (S), copper (Cu), zinc (Zn), nickel (Ni), molybdenum (Mo), chlorine (Cl). Out of these, C, H, O, N, P, K, Ca, Mg, and S are required by plants in higher amounts, so are called macronutrients, while remaining are required in smaller quantities, therefore, termed as micronutrients. Plant requirement of micronutrients is relatively low compared to macronutrients, but their deficiency in plants leads to the decreasing plant resistance to unfavorable environment followed by decreased yield and food quality. The deficiencies of micronutrients in crops have increased noticeably during recent decades due to the loss of micronutrients through leaching, erosion, intensive cropping, decreased use of animal manure and plant residues (Fageria et al. 2002).

The soil varies widely from region to region in their micronutrients content and in their ability to supply a sufficient quantity of these nutrients to plants (White and Zasoski 1999). Soil alkalinity is a condition of the soil that occurs as a result of an accumulation of soluble salts in soils having pH higher than 7. Soil alkalinity problem is commonly present in arid to semi-arid climates which cover about 25% of the earth (López-Bucio et al. 2000). Alkaline soils are saturated with calcium carbonate ($CaCO_3$), are highly porous, and freely draining (López-Bucio et al. 2000). The availability of micronutrients in the soil is affected by type of parent material, by soil biological and edaphic factors like pH, organic matter, redox potential, soil minerals reactions, soil microbial activity, and the interaction with coexisting ions (Masunaga and Marques Fong 2018). Different fertilization and agronomic practices can change the bioavailable concentration of these nutrients in the soil (Li et al. 2007). Various micronutrients behave differently in soil matrix depending upong their nature and extent of interaction with soil properties, some of important ones are explained ahead. Among all micronutrients, boron is found in low concentration in soil, mostly igneous rocks of the earth crust having an average concentration of 20 mg kg^{-1} can act as a potential source of B in process of soil formation. For soil bioavailable B concentration, desorption and adsorption of B on aluminum/iron and clay oxides surfaces controls the availability of B. The Fe concentration in soils is administered by oxides of iron such as magnetite (Fe_3O_4), hematite (Fe_2O_3), and goethite (FeO[OH]) (Masunaga and Marques Fong 2018). Chlorine occurs mostly in the form of Cl^- in plants and soil and it is an important micronutrient in higher plants because chlorine participates in many physiological metabolic processes of plants (Chen et al. 2010). Chlorine anion (Cl^-) does not readily make different complexes and it displays a minute affinity towards adsorption to soil components. Nickel is the fifth most occurring element on earth (Harasim and Filipek 2015) and is an abundantly found metal with 3% of the earth's crust (Magnitskiy 2011). Nickel mostly occurs in mineral forms such as niccolite, pentlandite, milarite, garnierite, and ullmannite and presents in two principal ore types, i.e. laterite and sulfide. In alkaline soils, high pH of soil contributes to form less available organic Mn complexes, which results in low availability of Mn in soil. Generally, copper is found in soils formed by the basic rocks and shales, from acid igneous rocks, sands, and sandstones. Copper is absorbed in the form of divalent ion Cu^{2+} by plants (Tabatabai et al. 2005). Copper is imperative for carbohydrates and nitrogen metabolism in plants, and thus insufficient Cu availability results in stunted plant growth. Copper is also necessary for the synthesis of lignin which is compulsory for the inhibition of wilting of the cell wall. The Mo availability in soil is affected by the concentration of lead (Pb^{2+}), and molybdate (${MoO_4}^{-2}$) ions; ${MoO_4}^{-2}$ also reacts with ferrous (Fe^{2+}), and Mn^{2+} to form iron-molybdate ($FeMoO_4$) and manganese-molybdate ($MnMoO_4$), respectively. In alkaline soil conditions, $FeMoO_4$ and $MnMoO_4$ are soluble, which makes Mo more available. Zinc forms complexes with sulfate (${SO_4}^-$), nitrate (${NO_3}^-$), chloride (Cl^{-1}), phosphate (${PO_4}^{-3}$). Zinc sulfate ($ZnSO_4$) is very important in soil as it contributes to the Zn concentration in soil solution. In neutral to alkaline soils, zinc hydrogen phosphate ($ZnHPO_4$) can prove important regarding Zn availability to plants depending on phosphate concentration (Masunaga and Marques Fong 2018).

Micronutrients are considered essential elements for life and their vital role in the maintenance of balanced physiology of plants makes them limiting nutrient as well. Some micronutrients are cofactors for different enzymes related to the various biochemical and cellular phenomenon (Barker and Pilbeam 2015). To cope with the problem of less availability of different micronutrients in alkaline soils, we can apply them in soluble forms (metal chelates) or directly to the plants (foliar application). We can also deploy some factors that directly influence the availability of the micronutrient like alteration of pH by liming (for acidic soils) and adding gypsum for sodic soils, altering redox potential (by controling aeration and irrigation), biological activity (by use of crop residue, manure), application of organic matter, and adopting crop rotation. The selection of these practices should be according to the farmer's access to information and materials, keeping in view their affordability for adopting these practices and strategies. Contents ahead are detailed aspects of micronutrient sources, clasification, issue related to bioavalibility and possible solutions to cope nutrient dificiency in alkaline soil.

16.2 Sources and Classification of Micronutrients in the Environment

Micronutrients play their role in the functioning, growth, and development of humans as well as plants (Nakandalage and Seneweera 2018). When micronutrients are dissolved in the form of ions or chelates in soil solution, they are available for uptake by plants. However, micronutrients dissolved in soil solution react with various compounds (carbonates and phosphates) to form chemical precipitates or to form complexes to become unavailable to plants (Yujun et al. 2002).

16.2.1 Boron

Boron (B) is a significant micronutrient for plants but it appears toxic when applied in excessive amounts (Kot 2015). Boron belongs to the third group of the periodic table and is considered a metalloid like arsenic (As), silicon (Si) which shows their properties in between the nonmetals and metals (Nable et al. 1997). Boron concentration ranges around 10 mg kg^{-1} (milligram per kilogram) in earth crust and seawater it ranges about 4.5 mg kg^{-1} (Kot 2015). Boron is usually not commonly present in free elemental form in nature as it is found in combination with different elements like borates and other compounds with oxygen with prominant oxidation state of III (B^{3+}). The average concentration of boron is about 20 mg kg^{-1} in soil, and boric acid (H_3BO_3) is a predominant and available form of B which is readily available for plants at pH ranging from 5 to 9 (Masunaga and Marques Fong 2018).

Geothermal activities and volcanic eruptions are some big sources responsible for the release of boron to the atmosphere and water bodies. Likewise, the anthropogenic activities (mining, agricultural fires, fossil fuel burning) and rock weathering are the minor contributors of B to the atmosphere (Kot 2009). In surface waters, B is added by precipitation and underground water drainage.

16.2.2 Zinc

Zinc is an essential micronutrient for plants and humans and it has an important role as a structural, catalytic, and regulatory cofactor for many enzymatic reactions (Montalvo et al. 2016). Zinc is necessary for the maintenance of cell membranes integrity, metabolism of carbohydrates, and synthesis of protein and growth hormones, i.e. indoleacetic acid in plants (Broadley et al. 2012). Predominantly, Zn in plants is absorbed in the form of Zn^{2+}, and as zinc hydroxide ($ZnOH^+$) from soil with high pH (Broadley et al. 2012). Soil organic matter has an important effect on Zn availability as the two forms of organic matter (soluble and solid) have opposing effects on the availability of Zn. Other sources of Zn are sphalerite (Zn sulfide-Zn ore) and Zn oxide which are being used in industry (Sandstead 2015).

Zinc is usually found in surface and groundwater, enters the environment from different sources including municipal wastes, mine drainage, industrial wastes, urban runoff, and from erosion of soil particles containing Zn content. Sources of Zn are largely anthropogenic resulting from industries emissions and automobiles (Goldman 2009). The concentration of Zn is found around 80 mg kg^{-1} in the lithosphere and average concentration in soil is 90 mg kg^{-1} (Masunaga and Marques Fong 2018).

16.2.3 Copper

Copper is a micronutrient that is found abundantly in several minerals and rocks and is considered necessary for many metabolic activities in prokaryotes and eukaryotes (Sun et al. 2014). It comprises about 6 parts per million (ppm) of the earth crust (Riedel 2008). Copper has properties of a transition element, which is redox-active and plays its specific role in nitrogen and carbon metabolism, photosynthesis, respiration, and protects plants from oxidative stress (Broadley et al. 2012). Naturally occurring Cu is found as monovalent (Cu^+) and divalent (Cu^{2+}) forms. Due to its heavier density (>5 g cm^{-3}), Cu has been recognized as heavy metal (Sağlam et al. 2016). Copper is an important micronutrient for the metabolism and growth of plants as it has a key role in carbohydrates distribution, physiological processes, and protein metabolism.

Smelting and mining processes are the major sources for the release of Cu in the environment, where the concentration of Cu could be 700–4000 mg kg^{-1} close to its mining industries (Printz et al. 2016)· Copper is being mined in every continent except Antarctica. Apart from mining, the frequent use of copper-based fungicides is also a big source of copper in soils. Elemental Cu in earth crust is found bonded with different Cu ores throughout the world including Asia, Africa, South America, Europe, and North America as the ores of Cu are found in basaltic rocks with its commonly found ore type chalcopyrite (Riedel 2008).

Table 16.1 Fate of micronutrients in soil and plants

Nutrient	Uptake form	Mobility in soil	Mobility in plants
Boron	BO_3^-, H_3BO_3	Mobile	Immobile
Zinc	Zn^{2+}	Immobile	Immobile
Copper	Cu^{2+}	Immobile	Immobile
Iron	Fe^{2+}, Fe^{3+}	Immobile	Immobile
Nickel	Ni^{2+}	Partially mobile	Mobile
Molybdenum	MoO_4^-	Partially mobile	Immobile
Manganese	Mn^{2+}	Mobile	Immobile
Chlorine	Cl^-	Mobile	Mobile

Source: https://nrcca.cals.cornell.edu/soilFertilityCA/CA1/CA1_print.html; http://www.icontrolpollution.com/articles/nickel-its-availability-and-reactions-in-soil.pdf

16.2.4 Iron

Iron (Fe) comprises about 5% of the lithosphere making it the fourth major constituent of earth's crust having an average concentration of 40 g kg^{-1} in soils (Masunaga and Marques Fong 2018). Iron is said to be the second most plentiful metal on earth after aluminum (Broadley et al. 2012). The main mineral of Fe is ferromagnesium, which releases iron in the atmosphere through weathering, and forms precipitates of Fe as ferric oxides and hydroxides. The Fe concentration in soil is primarily administered by oxides of Fe^{3+} such as hematite (Fe_2O_3), magnetite (Fe_3O_4), and goethite (FeO[OH]) (Broadley et al. 2012). Table 16.1 shows the nature of various micronutrients in soil and plant systems.

16.2.5 Nickel

Nickel is the fifth abundantly present element on earth after oxygen, iron, magnesium, and silicon (Harasim and Filipek 2015). Nickel exists in various oxidation states and its predominant oxidation state in normal environmental conditions is Ni^{2+} and other valences of Ni (−1, 1+, 3+, and 4+) also exist, but less frequently (Coogan et al. 2008). Nickel is associated with Fe and Cu geochemically, and the soils having high contents of Fe and Cu generally occupy a large amount of Ni. Mobility of Ni is directly dependent on the texture composition and structure of soil mineralogy (Kabata-Pendias 2004).

Nickel exhibits an extensive occurrence in the environment, as Ni is a key constituent of about 100 minerals, and these minerals have numerous commercial and industrial uses (Cempel and Nikel 2006). Natural sources of Ni in the environment are forest fires, wind-blown dust, and volcanic emissions. Anthropogenic sources involved in the atmospheric release of Ni are the combustion of fuel oil, coal, diesel, and the incineration of sludge and waste. Nickel takes part in some important metabolic reactions like hydrogen metabolism, acetogenesis, ureolysis (N metabolism), and methane biogenesis (Mulrooney and Hausinger 2003).

16.2.6 Molybdenum

Molybdenum (Mo) is a micronutrient that is required mainly for the synthesis and activity of the enzymes that reduce NO_3^- to ammonium (NH_4^+) in plants, and also essential for the activity of biological N-fixation by rhizobia (McGrath et al. 2014). Molybdenum is found mainly in the form of molybdate oxyanion (MoO_4^{-2}) in its oxidized form (Broadley et al. 2012). The amount of Mo present in soil and the amount of Mo required by plants are relatively very small. In higher plants, some enzymes containing Mo as a cofactor have been found, and Mo has both catalytic and structural functions in these enzymes and is involved in redox reactions (Marschner 1995).

Molybdenum is present in the lithosphere in an average concentration of 2.3 mg kg^{-1} (Masunaga and Marques Fong 2018). Molybdenum is used to produce steel, alloy, lubricants, plastics, and pigments and is also used as a chemical catalyst.

16.2.7 Manganese

Manganese is considered as an important micronutrient and commonly found in the form of Mn^{2+}, but it usually gets oxidized to other forms Mn^{3+} or Mn^{4+} (Blasco et al. 2018). Manganese has a substantial role in different redox reactions in plants due to these varriable oxidation states (Broadley et al. 2012). Manganese plays a vital role in the chloroplast formation directly or indirectly, and also contributes to organizing the lamellar system of chloroplasts (Zanão Júnior et al. 2010), making it vital for photosystem II (an oxygen-evolving process in photosynthesis) (Goldman 2009). The abundantly available Mn form in a soil solution is Mn^{2+}, which is present in the range of 0.01–1.0 mg l^{-1} and rises by lowering the soil pH. Liming relatively reduces the Mn uptake due to Ca^{2+} provision and altering pH of acidic soils. The concentration of manganese in the lithosphere is predicted to be about 1000 mg kg^{-1} (Masunaga and Marques Fong 2018). Manganese is present commonly in lake systems worldwide and its sources are ranging from the deposition of industrial pollutants to the deposition of soil and dust particles (Goldman 2009). Some concentration of Mn is released into the atmosphere in the form of fly ash and is deposited on lakes and land downwind of the plant.

16.2.8 Chlorine

Chlorine is considered a micronutrient in some higher plants and plays a key role in the physiological processes of plants. Natural sources of Cl to soil are mainly sea spray, rainwater, air, and dust pollution and various anthropogenic sources (White and Broadley 2001) and occur mostly in the form of Cl^- (Chen et al. 2010). Sources of organic chlorine also subsidize the deposition of Cl in soils. These anthropogenic sources include chlorination of soil, de-chlorination of organic compounds, and the disposal of household waste (White and Broadley 2001). Anthropogenic sources of organochlorines are comprised of herbicides (xenobiotics), artificial sweeteners, pharmaceuticals, and pesticides.

16.3 Chemistry of Micronutrient in Normal and Alkaline Soils

Recent advances in the field of chemistry and availability of micronutrients are tough to generalize because of their vast diversity in their (nutrients) chemical properties, the ability of roots of plants to absorb micronutrients, and their reactions with soil. In general, different nutrients behave differently in soil and plant upon accumulation as described in Table 16.1. The existence of micronutrients usually rivals the age of parent materials and the effect of type, vegetation, and various soil formation factors, and climatic conditions during weathering (Harmsen and Vlek 1985).

16.3.1 Boron

Boron exhibits the diverse and unique chemistry of any element except C (Greenwood and Earnshaw 1984) because B has only three electrons in the valence shell, which are when combined in three pairs leave a p-orbital unfilled in the valence shell. Boron, directly and indirectly, takes part in many soil processes, i.e. illuviation and the creation of colloids, isomorphic substitution of minerals, soil biological cycle, and humification (Kot 2015). Boron occurs naturally as boric acid H_3BO_3 in solution, which is a weak mono-basic acid and acts as an electron acceptor. Boron is found in soil solution as a non-ionized molecule on pH ranges of soil suitable for plant growth (Fageria et al. 2002). Boron exhibits low adsorption at low pH, and it increases with an increase in pH (Masunaga and Marques Fong 2018). The availability of B is usually high at pH 5.5–7.5, and its availability decreases with an increase or decrease in soil pH (Fageria et al. 2002). Different anionic forms of B like HBO_3^{-2} (perboric acid), $H_2BO_3^{3-}$ (dihydrogen borate), $B_2O_7^{-2}$, and BO_3^{-3} (borate) also exist at soil pH higher than 7. At high pH, adsorption of B on precipitated $Al(OH)_3$ (aluminum hydroxide) increases, which decreases the availability of B in soil.

16.3.2 Zinc

Like other metallic ions, i.e. iron (Fe^{2+}), manganese (Mn^{2+}), and copper (Cu^{2+}), the zinc (Zn) has a divalent cation (2+) with its complete “d” orbital; but, Zn has no redox activity. On average, Zn ranges about $10^{-2.21}$ M (molar) in a soil solution at 10% moisture condition. Franklinite ($ZnFe_2O_4$) aids in the solubility of Zn^{2+} represented by available Zn in soil (Masunaga and Marques Fong 2018). The concentration of Zn in the soil is negatively related to the pH of the soil due to its stronger sorption property at high pH with solid phase (Jeffery and Uren 1983). Zinc is mainly adsorbed in exchangeable forms as Zn^{2+}, $ZnOH^+$, and $ZnCl^+$ on clay surfaces and organic matter, and additionally, cation exchange sites, it makes complexes and chelates, which are highly soluble. At high pH, Zn is absorbed in the form of Zn^{2+}, and are often taken up as $ZnOH^+$ by plants (Broadley et al. 2012). Zinc also tends to form soil complexes with nitrate, phosphate, sulfate, and chloride, and complexes of $ZnSO_4$ have a significant role in the soil as they contribute to Zn in neutral to alkaline soil. Zinc-HPO_4 can be important in this regard depending on its phosphatic reactions (Masunaga and Marques Fong 2018).

16.3.3 Copper

Copper (Cu) is a transition element that has 1 or 2 stable ions and incomplete "d" orbital having some similarities in properties with Fe, such as easy electron transfer and highly stable complexes formation. These partly filled "d" orbitals allow the Cu to form complexes taking place in redox reactions (Migocka and Malas 2018). Many features of Cu as a micronutrient are based on enzymatically bounded copper, which catalyzes various redox reactions (Broadley et al. 2012). According to some adsorption and fractionation studies, Cu is linked closely with oxides of Al and Fe; similar to most metals at higher pH values. Copper is more extensively absorbed by soil colloids, but the availability of Cu to plant is not much sensitive to pH as in the case of other metals due to the formation of Cu-organic complexing (Tabatabai et al. 2005). Copper adsorption is influenced by the pH of the soil, and adsorption of this metal ion increases with increasing pH. Maximum adsorption of Cu occurs at the pH range of 5–7. At low pH values, the concentration of $SO_4{}^{2-}$ is the main factor which regulates the copper availability in the soil. At high pH of plant, partial pressure of CO_2 and pH are the key controlling factors (Masunaga and Marques Fong 2018).

16.3.4 Iron

Iron is the second most plentiful metal on the earth after aluminum and occurs in two oxidation states Fe^{2+} and Fe^{3+}. Iron exists in nature as primary and secondary minerals of aluminosilicate and as oxyhydroxide minerals, such as Fe_2O_3 and FeOOH (Vance 2005). Commonly found mineral of Fe is ferromagnesium, which releases Fe through weathering and released precipitates are ferric oxides and hydroxides (Masunaga and Marques Fong 2018). Generally, the solubility of Fe in the soil is low, particularly in aerated alkaline soil solutions, as in some aerated soil systems in the physical range of pH and the concentration of Fe^{2+} and Fe^{3+} is lower than 10^{-15} M due to the oxides, oxyhydroxides, and hydroxides of Fe (Lemanceau et al. 2009). In aerated soils, the predominant form of iron is Fe^{3+}, which is noticeably low (at pH range 4 to 8, 10^{-9} to 10^{-20} M) as likened to the cations of other micronutrients like Cu, Zn, and Mn (Masunaga and Marques Fong 2018). Iron shows the least solubility at pH from 7.4 to 8.4, at which Fe deficiencies occur in plants. In alkaline soil solutions, ferrous iron shows high solubility in water and the Fe^{2+} species hydrolyzed to $FeOH^+$.

16.3.5 Nickel

Nickel is an abundantly found metal in the earth, which comprises about 3% of the earth's crust. In agricultural soils, the concentration of Ni varies from 3 to 1000 mg kg^{-1} (Magnitskiy 2011). Naturally, Ni is present in two main ore types, laterite and sulfide, occurring mostly in different mineral forms like garnierite, pentlandite, millerite, ulmannite, and niccolite (Harasim and Filipek 2015). Mobility of Ni mainly depends on the soil pH, and soil type and its site-specific, which increases at low pH. The mobility of Ni is low under neutral to alkaline soil and reducing conditions, but nickel can be quite mobile in acidic and organic matter rich soils (Harasim and Filipek 2015). In most soils, Ni tends to bind with some ion-exchange sites, and it is adsorbed on or coprecipitated with Al and Fe oxyhydroxides. Nickel participates in metabolic reactions, methane biogenesis, ureolysis, and hydrogen metabolism (Mulrooney and Hausinger 2003).

16.3.6 Molybdenum

Molybdenum is an important micronutrient for both animals and plants, usually found in relatively low concentrations in the diet, but excessive consumption of Mo can happen from edible crops grown on Mo containing soils or from that area with excess smelting and mining operations. Naturally, Mo does not occur in its native state and exists in numerous oxidation states in the form of minerals, which are obtained from water-insoluble ores like ferrimolybdite $Fe_2(MoO_4)_3$, wulfenite ($PbMoO_4$), molybdenite (MoS_2), and powellite ($CaMoO_4$) (Tallkvist and Oskarsson 2015). The average Mo concentration in soils is about 2 mg kg^{-1}, while in the lithosphere, its value is about 2.3 mg kg^{-1}. Among other micronutrients, Mo is the only nutrient, whose availability increases with increasing the pH of soil. The most abundant form of molybdenum is $MoO_4{}^{2-}$, which can polymerize in soil solution (Fageria et al. 2002). Metabolism of Mo is disturbed by S and Cu intake in some species (Tallkvist and Oskarsson 2015). Molybdenum is commonly used in the manufacturing of fertilizers, suppressants, pigments, smoke corrosion-resistant steel, oxidation catalysts, smoke suppressants, lubricants, and metal alloys (Hall 2018).

16.3.7 Manganese

Manganese in the soil can be found as exchangeable and dissolved Mn^{2+} and in the form of insoluble Mn^{3+} or Mn^{4+} (Graham 2004). In soil solution, the most common form of Mn is Mn^{2+}, which is found about 0.01–1.0 mg l^{-1} on average and this concentration rises by lowering the pH and redox potential below −200 mV (Masunaga and Marques Fong 2018). Both the pH and redox conditions affect the bioavailability of Mn in soils. In acidic soils, at increased redox potential and low pH <5.5 of soil, Mn oxides are reduced, which increases the Mn^{2+} concentration in soil

(Watmough et al. 2007). Other forms of Mn such as Mn^{3+} and Mn^{4+} dominate at high pH, which is the minimum available and it cannot get accumulated in plants (Rengel 2000). Increased concentrations of Mn accumulated in the tissues can alter different processes in plants like absorption, the activity of enzyme, and translocation of minerals (P, Mg, Fe, and Ca), which cause oxidative stress in plants (Dučić and Polle 2005).

16.3.8 Chlorine

Chlorine is a micronutrient in higher plants necessary for growth and readily contributes to plant physiological processes and occurs mainly as Cl^- in plants and soil (Weggler et al. 2004). Movement of Cl in the soil is typically related to water changes and the association present between evapotranspiration and precipitation. Soil minerals mostly have a negative charge so Cl does not readily form complexes and is mostly repelled from the soil particles surfaces. So, the concentration of Cl in bulk solution is always more than the Cl concentration present in the layers surrounding the soil particles (Chen et al. 2010). Chlorine also functions as counter anion and stabilizes the potential of the membrane and it also functions in pH and turgor regulation (Broadley et al. 2012).

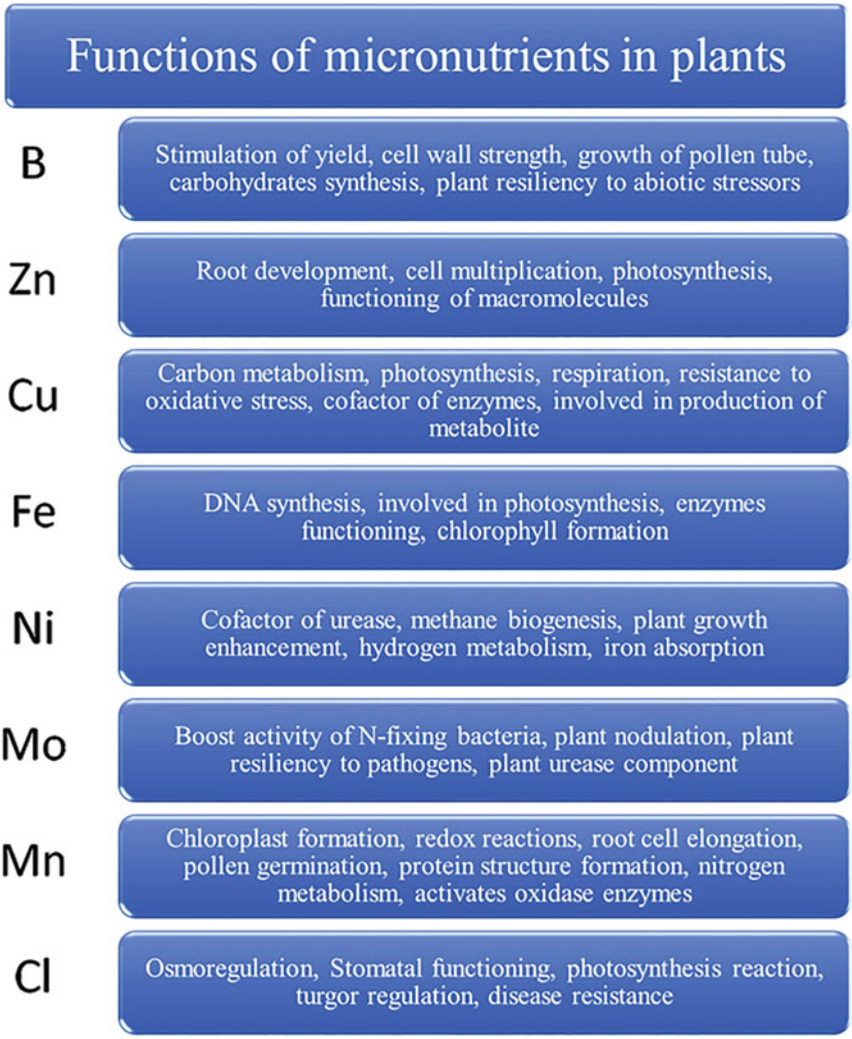
16.4 Role of Micronutrients in Plant Growth and Yield

Adequate crop nutrition management is an important prerequisite for dynamic and healthy crops. For this, crop nutrients are considered one of the *burning factors for high yield of crops as they are required in varying quantities*. Micronutrients are vital elements needed for plant growth and have a specific role in plant physiology and metabolism which is linked with the amount and availability of these micronutrients in the soil. The general role of micronutrients in plants is described in Fig. 16.1.

16.4.1 Boron

Boron is considered essential for many plant processes like the growth of pollen tubes, pollen propagation, the establishment of the cell wall, and the growth of new cells in meristematic tissue (McGrath et al. 2014). Boron is also implicated in main plant processes like supporting metabolic activities and maintaining cell wall structure (Kot 2015).

Although B is not required in high amounts by plants, its deficiency can cause serious growth problems if not provided at appropriate levels, while the excess amount of B is reported harmful to different plant species (Chapman et al. 1997). However, specific plants vary greatly for B demand and some proved to be tolerant of excess B concentration. Boron plays a significant role in the carbohydrate



Functions of micronutrients in plants

B	Stimulation of yield, cell wall strength, growth of pollen tube, carbohydrates synthesis, plant resiliency to abiotic stressors
Zn	Root development, cell multiplication, photosynthesis, functioning of macromolecules
Cu	Carbon metabolism, photosynthesis, respiration, resistance to oxidative stress, cofactor of enzymes, involved in production of metabolite
Fe	DNA synthesis, involved in photosynthesis, enzymes functioning, chlorophyll formation
Ni	Cofactor of urease, methane biogenesis, plant growth enhancement, hydrogen metabolism, iron absorption
Mo	Boost activity of N-fixing bacteria, plant nodulation, plant resiliency to pathogens, plant urease component
Mn	Chloroplast formation, redox reactions, root cell elongation, pollen germination, protein structure formation, nitrogen metabolism, activates oxidase enzymes
Cl	Osmoregulation, Stomatal functioning, photosynthesis reaction, turgor regulation, disease resistance

Fig. 16.1 Functions of micronutrients in plants. Source: Figure is made by authors using information provided and compiled by Taiz and Zeiger (2006) and Ahmad and Ashraf (2012)

synthesis and its translocation towards meristem regions of top and root across the membrane. Other studies disclosed that B is important for differentiation, development, maturation, cell division, and growth near the tips of shoots and roots (Dear and Weir 2004). The deficiency of boron hampers fruiting and flowering by impeding pollen tube development and pollen germination processes (Muntean 2009). Its deficiency also reduces the soil fertility and fruiting becomes slow or non-existent which depends upon the severity of B deficiency (Muntean 2009).

16.4.2 Zinc

Zinc is required in fewer but critical quantities by plants or animals and normally found in association with Cu and Pb. Zinc is crucial for the structure and normal functioning of different macromolecules (Alloway 2009). Zinc takes part in controlling cellular growth, differentiation, and gene expression because it contributes as a cofactor in more than 120 enzymes. Zinc also has its role in photosynthesis, cell multiplication, auxin formation in plant, and regulation of nitrogen metabolism (Shier 1994). It is also very important in the metabolism of plants by promoting the activities of hydrogenase, synthesis of cytochrome, and stabilization of ribosomal fractions.

Zinc is required normally in low concentration by plant and if the available amount of Zn is not appropriate, it will lead to the physiological stress that happens due to dysfunction of enzymes and other Zn dependent metabolic functions (Alloway 2009). Its deficiency in plants results in the expression of irregularities which become visible as symptoms of deficiencies such as chlorosis, spikelet sterility, stunted growth, and smaller leaves (Cakmak 2000).

16.4.3 Copper

Copper is an essential micronutrient for the normal growth of a plant, although it is considered potentially toxic in higher concentrations and plays a basic part in plant health and nutrition (Priyanka et al. 2019). Copper is needed in the structural and catalytic constituents of different enzymes and proteins responsible for oxygenation reactions, electron transfer, and charge accumulations (Cook et al. 1998). Copper takes part in plant growth as a cofactor and prosthetic group of different enzymes involved in different metabolic pathways as well as ATP synthesis (Vinit-Dunand et al. 2002). Copper participates as a basic structural element in many metalloproteins, some of which are involved in electron transport in mitochondria and chloroplasts in response to oxidative stress in plants. The deficiency of Cu in crops is widespread and occurs all over the world, particularly in high pH soils having high organic carbon content and poor drainage conditions (Gupta et al. 2008). Deficiency symptoms of Cu occur on the newer leaves and start with slight chlorosis in between the veins of the new leaves which leads to the death of apical meristems, inhibiting the growth of lateral branches.

16.4.4 Iron

Iron is an important micronutrient for animals and plants because of its key role in several metabolic processes like photosynthesis, DNA synthesis, and respiration (Rout and Sahoo 2015). In neutral to alkaline soils, iron is not commonly available in normal conditions, executing plant's iron-deficiency despite its abundance. In the synthesis of chlorophyll, iron acts as a catalyst and is involved in reduction and oxidation reactions during photosynthesis and respiration (McGrath et al. 2014). Iron is the main constituent of several pigments and enzymes and assists in the reduction of sulfate and nitrate, and energy production within the plant. Although Fe is not used in the synthesis of chlorophyll, it is necessary for the development of chlorophyll. Iron acts as a cofactor for several enzymes essential for hormone synthesis of plants, acid-1-carboxylic oxidase, lipoxygenase, ethylene, and 1-aminocyclopropane (Siedow 1991). Iron is also necessary for the development of the porphyrin structure of chlorophyll so it is a key constituent of chloroplasts (Rout and Sahoo 2015). Mitochondria contain a vast number of metalloproteins in plants that are directly dependent on Fe to continue their functioning (Bertini and Rosato 2007).

Deficiency of Fe in plants decreases the growth, yield, and quality of produce (Abadía et al. 2011). The deficiency of Fe in plants is expressed as interveinal chlorosis in new leaves (leaves are yellow with green veins).

16.4.5 Nickel

Nickel is considered to be the component of urease, which is involved in urea hydrolysis. It also improves the activity of hydrogenase, contributes to redox reactions, and excites the germination and growth (Fageria et al. 2002). Nickel also acts as a cofactor to enable urease to catalyze the conversion of urea into ammonium ions, which can be used as a source of N by plants and without Ni, conversion of urea is impossible (Sirko and Polonica 2000).

Nickel readily participates in methane biogenesis, hydrogen metabolism, and acetogenesis (Mulrooney and Hausinger 2003). Small amounts of Ni in plants also contribute to the synthesis of phytoalexin, and thus deliberate resistance to various diseases and environmental stresses.

16.4.6 Molybdenum

Molybdenum is an important micronutrient for crop production, which has its specific role in crop resilience to pathogens, stimulation of yield, support of the emergence of seedlings, seedling growth, and improvement in seed quality (Dimkpa and Bindraban 2016). Molybdenum is an essential constituent of N_2-fixation enzymes (nitrate reductase), which are required for normal assimilation of nitrogen (Fageria et al. 2002). Alike other micronutrients necessary for plant growth, Mo is utilized specifically by plant enzymes to participate in reduction and oxidation reactions (Kaiser et al. 2005). Molybdenum is a biologically inactive element, typically found as an important portion of organic pterin complex called the Mo cofactor. This Mo cofactor can bind with other Mo-requiring enzymes, which are called molybdoenzyme. They are present in biological systems like animals, plants, and prokaryotes (Williams and Fraústo da Silva 2002).

The deficiency symptoms of Mo in plants occur as bleaching and withering of leaves, stippled pale appearances in young leaves, and sometimes death of tips of leaves. Leguminous plants suffering from Mo deficiency show symptoms of poor seed production, pale green to yellowish leaves, and stunted growth (Fageria et al. 2002).

16.4.7 Manganese

Manganese is an imperative micronutrient that is required by both plants and humans. Available Mn in soil appears as primary and secondary minerals, which are sorbed onto the surfaces of minerals and organic matter, combined into soil solution and soil organisms (Fageria et al. 2002). Manganese is used in the formation of the structure of proteins and different photosynthetic enzymes (Millaleo et al. 2010). Manganese is involved as a catalyst in initiation for many enzyme systems and also catalyzes the formation of chlorophyll (McGrath et al. 2014). In plants, Mn triggers the functioning of many enzymes of the shikimic acid pathway which leads to the synthesis of many secondary products and aromatic amino acids like flavonoids and lignin (Broadley et al. 2012). Manganese in plants is also involved in root elongation, pollen tube growth, pollen germination, and resistance to root pathogens. An adequate amount of Mn in plants is critical, as Mn eases the photolysis of water molecules and provides energy for photosynthesis.

Manganese deficiency in plants happens when the soil medium pH exceeds by 6.5 as Mn tied up and become unavailable for uptake. Deficiency symptoms of Mn often look like the deficiency symptoms of Fe, i.e. interveinal chlorosis on newly formed leaves and sometimes with sunken and tan spots in the chlorotic areas between the veins and stunted plant growth.

16.4.8 Chlorine

Chlorine being the last micronutrient from the list is considered important for photosynthesis in plants and also acts as an activator of different enzymes. Chlorine takes part in the osmoregulation of plants grown on saline soils (Fageria et al. 2002). In plants, Cl is an important micronutrient for the stomatal functioning and opening of stomata. (Marschner 1995). A significant role of Cl^- is also considered in acid-base and charge regulation in relation to the form in which nitrogen is supplied, which tends to improve the water use efficiency (Raven 2017). Studies have shown that potassium chloride (KCl) boosted the profit of wheat and other crops. Several diseases were reported to be stifled in different crops by the application of Cl at the levels of macronutrient (Chen et al. 2010). Table 16.2 shows the role of various micronutrients on plant growth and yield.

Table 16.2 Role of micronutrients on plant growth and yield

Nutrients	Crop	Application method	Application rate	Effect on plants (% yield increased)		Reference
				% yield increase (grain/tuber/fruit)	% yield increase (shoot/straw biomass)	
Boron	Cotton	Soil	3 kg ha^{-1}	–	13	Ahmed et al. (2011)
	Sunflower	Foliar	250 mg l^{-1}	49	50	Al-Amery et al. (2011)
Zinc	Rice	Soil	7.5 mg kg^{-1}	97	–	Muthukumararaja and Sriramachandrasekharan (2012)
	Bean	Soil	10 kg ha – 1	–	–	Fageria (2001)
	Pomegranate	Foliar	0.6%	18	–	Hasani et al. (2012)
Copper	Wheat	Soil	1.5 mg kg^{-1}	63	26	Kumar et al. (2009)
	Rice	Soil	8 kg ha^{-1}	–	8.5	Fageria et al. (2002)
	Bean	Soil	8 kg ha^{-1}	–	32	Fageria et al. (2002)
Iron	Rice	Liquid (lab)	6.5 mg l^{-1}	–	–	da Silveira et al. (2009)
	Bean	Foliar	1 g l^{-1}	133	–	Elham et al. (2014)
	Soybean	Foliar	1 g l^{-1}	45	42	Sheykhbaglou et al. (2010)
Nickel	Corn	Liquid	0.05 mg l^{-1}	–	46	Gheibi et al. (2011)
	Lettuce	Foliar	25 μ Mol l^{-1}	–	356	Hosseini and Khoshgoftarmanesh (2013)
Molybdenum	Rice	Soil	2 kg ha^{-1}	13	24	Muthukumararaja and Sriramachandrasekharan (2012)
Manganese	Maize	Soil	20 kg ha^{-1}	–	16	Fageria et al. (2002)
	Bean	Soil	40 kg ha^{-1}	–	19	Fageria et al. (2002)
	Pomegranate	Foliar	0.6%	18	–	Hasani et al. (2012)
Chlorine	Rapeseed	Soil	1.4 g pot^{-1}	–	–	Podleśna (2012)

16.5 Factors Affecting the Bioavailability of Micronutrients to Different Crops

A wide range of soil and environmental factors are responsible for the transit of nutrients from soil to plants. Basic mechanism of micronutrient take-up is described in Fig. 16.2. A detailed description of various factors affecting nutrient availability to crop plants is given below.

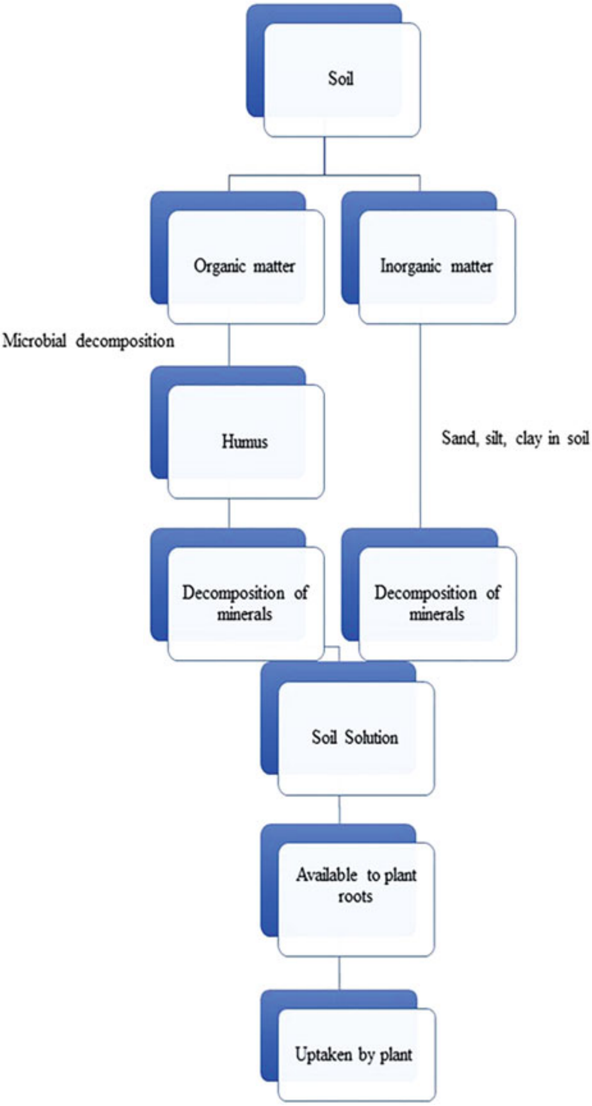


Fig. 16.2 Mechanism of micronutrients availability to plants as affected by various soil factors

16.5.1 Soil Physico-Chemical Properties

The bioavailability of Fe, Mn, Cu and Zn in soil usually decrease with increase of soil pH and avalibilty of Mo increases with increase of soil pH with B being an exception as initially its concentration decrease but at pH >8.5 it start increasing (Masunaga and Marques Fong 2018). At high pH range, all of these metals become precipitated as insoluble hydroxides and carbonates (except Mo), while Zn binds strongly to variable charge minerals via chemisorption (McGrath et al. 2014). Many soil factors such as pH, moisture, temperature, and soil organic matter affect the bioavailability of different micronutrients to plants. The comparative effects of these physical factors vary widely from one micronutrient to others (Fageria et al. 2002). Manganese, Zn, Cu, and Fe solubility decreases one-hundred times with an increase in each unit of soil pH (Halvin et al. 2005). Production of crops in alkaline soils with low soil organic matter content results in micronutrient deficiencies (Frossad et al. 2000; Meena et al. 2020a). The increased concentration of carbonates and bicarbonates in soil solution also reduces the availability of micronutrients, where more bicarbonate (HCO_3^-) and hydroxide (OH^-) in the rhizosphere consequently increase the pH of the plant sap to a level that causes the precipitation of micronutrients thus lowering micronutrients availability as a whole (Malakouti 2008).

Soil pH and redox potential have a great effect on the phyto-availability of metallic micronutrients in soil (Dhaliwal et al. 2019). Soil pH and organic matter, CEC, CCE, clay and sand contents are important factors governing micronutrient concentration in soil (Sharma et al. 2004). Besides these direct factors, soil moisture, agronomic practices, and environmental factors are also involved in controlling soil nutrient concentrations. The application of fertilizers in alkaline soils can be a fissile option as they tend to modulate soil rhizosphere pH. Nitrogenous fertilizers tend to vary rhizosphere pH once applied in an accurate amount and with an effective method (Dhaliwal et al. 2019). The joint application of phosphorus with nitrogen presented a significant growth of Fe and Zn in the soil, while the insignificant result was detected with Mn and Cu (Setia 2004). However, the high phosphorus content of soils or high phosphatic fertilization of soil can decrease the availability in the case of Zn and other nutrients (Kizilgoz and Sakin 2010).

16.5.2 Soil Microbial Community

Soil microbial community is considered the most significant component of the environment, which helps to raise the efficiency of soil and hence increases the plant growth. A vast range of microorganisms is present in the soil with different nature of beneficial effects like PGPR, soil fungi as arbuscular mycorrhizal fungi and nitrogen-fixing bacteria. The beneficial activities of soil microorganisms are enhancement of the nutrient cycles, mineralization of organic matter (Fan et al. 2005) and interacting with soil microorganisms, improving the structure of soil (Egamberdiyeva 2007), controlling different pathogens (Mendes et al. 2011), and synthesis of biochemicals like hormones and enzymes (Compant et al. 2010). Plant growth-promoting rhizobacteria are a group of free-living bacteria that live in the rhizosphere and help improve plant growth. They are frequently in contact with the root surface which raises the crop yield by numerous mechanisms, e.g. disease suppression, improved nutrition, and phytohormone production. They also pose a solid impact on the development of arbuscular mycorrhizal fungi (Linderman 1997).

Soil microorganisms also alter the micronutrients solubility, hence increase or decrease the bioavailability of the micronutrients in the soil by affecting plant metabolism, alteration in the root exudates by symbiotic association, and cooperating with other microbial community (Fitter et al. 2011). It is commonly seen that soil microorganisms are capable to reduce the negative effects of micronutrients on plant growth and the environment under sufficient concentration of micronutrients by activating numerous mechanisms (Zhuang et al. 2007) as microorganisms affect the morphological and physiological properties of plants (Miransari 2013). Soil microbes like *Pseudomonas* spp. have a special ability to affect the soil micronutrient availability by producing carboxylates, which can chelate humic substances (riboflavin and quinones) and different micronutrients which can dissolve mineral oxides (Johal and Huber 2009).

16.5.3 Plant Symbiotic Associations

The conquest of land by plants was originated by the recruitment of symbiosis of fungal roots, thus founding the theory of mycorrhizal symbiosis around 450 million years ago (Field et al. 2015). A mutual association between soil-borne fungi and plant roots is called mycorrhizae, in which mycorrhizal fungi transport essential nutrients to the host plant and get some sugars and lipids in exchange. Even today, major plant species still form an association with mycorrhizal fungi for nutrients supply (Brundrett and Tedersoo 2018). The most common forms of mycorrhiza are ectomycorrhizal (EcM) and arbuscular mycorrhizal (AM) symbioses (Ruytinx et al. 2019).

To balance the concentration of micronutrients in their tissues, plants develop different strategies, modification of root architecture, altering the chemistry of root exudates, and collaboration with other soil microorganisms such as EcM and AM fungi (Ferrol et al. 2016). Fungi play a double role (for micronutrients bioavalibility) by avoiding them to accumulate in tissues of plants in polluted soils or by improving their mobility in limiting conditions (Ruytinx et al. 2019). The mycorrhizal association also helps plants to alleviate stress conditions induced by different micronutrient toxicity by activating different mechanisms of detoxification (Bui and Franken 2018). This helps plants in growth, to attain fitness and ensures crop quality improvement. The key role of these fungi is also considered in phytoremediation and different biofortification practices (Watts-Williams et al. 2013; Jangir et al. 2017). Different crops inhibited by AM fungi like soybean (*Glycine max)*, barley (*Hordeum vulgare*), maize (*Zea mays*), tomato (*Lycopersicon esculentum*), and pepper (*Capsicum*) displayed high concentrations of Zn compared with non-mycorrhizal crops in Zn-limiting or controlled conditions (Watts-Williams et al. 2015). Symbiotic associations of various organisms are very important in integrated nutrient management in soil (Degola et al. 2015).

16.5.4 Crop Root Exudates Production and Rhizosphere Chemistry

Root exudates are a set of different substances found in the rhizosphere that are released by plant roots and then modified by microbes. Root exudates are mixtures of many soluble organic compounds that contain sugars, enzymes, amino acids, organic acids, and other substances (Koo et al. 2004). Exudates released by roots contain different molecules that work as chemo-attractants for several PGPR. These molecules perform specifically to attract different cognate bacteria and also alter soil chemical properties (Beauregard 2015; Meena et al. 2020) which can make micronutrient avalibility more. Root exudates have properties to serve as a carbon source to provide nutrition and energy to the bacteria to reproduce in the rhizosphere (Beauregard 2015).

16.5.5 External and Plant Factors

Various external plant factors directly or indirectly affect the availability of micronutrients. Plant physiological and biochemical factors influence the availability of micronutrients by enzymes (ferrioxamine b, rhodotorulic acid, carbonic acid anhydrase, ascorbic acid oxidase), excretion of H^+, HCO_3^-, OH^-, root exudates (malic, citric, trans aconitic acids), and phyto-siderophores. Moreover, adaptations of plants against different stress or disease conditions like drought, acidity, or pests attack also cause to disturb the micronutrient contents. Factors like compaction, moisture stress, texture, pH, temperature, crop rotation, and agronomic practices are the main external factors that influence the availability of micronutrients to crops.

16.6 Constraints/Challenges Associated with the Bioavailability of Micronutrients in Alkaline Soils

16.6.1 Recovery of Micronutrients

Alkali soils are present in arid to semi-arid regions of the world typically in areas having poor drainage systems. The concentration and composition of soil micronutrients in soil affect the soil's physical properties and growth of plants through specific ion toxicity and osmotic power. Alkaline soils have a large percentage of cation exchange sites (CES) occupied by the undesirable ions of sodium (Na^+). Alkaline soils are characteristically freely draining, highly porous and saturated with free $CaCO_3$ (López-Bucio et al. 2000). This free $CaCO_3$ controls the chemistry of alkaline soils as alkaline pH reduces the solubility of micronutrients except for Mo, $CaCO_3$ fixes micronutrient cations and low concentration of organic matter in soil solution limits micronutrient replenishment (Rashid and Ryan 2004). The deficiency of Zn is the most dominating issue in alkaline-calcareous soils (Cakmak et al. 1998). Soil calcareousness, exposed subsoils, low organic matter, alkaline pH of the soil, Zn-free fertilizing, sandy texture of the soil, and flooding induced electro-chemical changes are certain factors that induce Zn deficiency in alkaline soils (Cakmak et al. 1998). Zinc deficiency can be encountered with a high level of application with fertilizers or foliar feeding with appropriate zinc sources. Deficiency of Fe is considered as the second most important disorder related to micronutrients in high pH soils as it is influenced by a high concentration of soil HCO_3^- in calcareous soils (Rashid and Ryan 2004). Recovery of Fe by soil fertilization could be difficult as soluble Fe salts lose their efficiency due to immediate oxidation of Fe^{2+} to Fe^{3+} insoluble form in alkaline soils. The deficiency of Cu and Mn found to be occasional in alkaline soils as available content of Mn in common soils is normally sufficient to the standard level that is considered satisfactory (NFDC 1998). Molybdenum availability is generally high in alkali soils, so a deficiency of Mo in alkaline soils is not a problem (Rashid and Ryan 2004). Acidification of soil for lowering the pH is an effective approach to raise the availability of micronutrients in alkaline soils (Table 16.3). Additions of a significant amount of organic matter could also play its role to acidify the soil as the microbial community decomposes the material, thus releasing some amount of CO_2, which then forms carbonic acid. Acidifying fertilizers application like ammonium sulfate can also assist to lower the soil pH to make sure the maximum availability of all micronutrients in alkaline soils.

Table 16.3 Average availability of micronutrients in alkaline soil and plant shoot dry matter

Nutrient	Average availability in alkaline soil (mg kg^{-1})	Average concentrations present in plant shoot dry matter adequate for growth (mg kg^{-1})
Boron	0.24[a]	20[d]
Zinc	1.07[a]	20[d]
Copper	1.70[a]	6[d]
Iron	13.17[a]	100[d]
Nickel	4.89[c]	0.1[d]
Molybdenum	0.1[b]	0.1[d]
Manganese	11.22[a]	50[d]
Chlorine	–	100[d]

[a] Nazif et al. (2006)
[b] Carroll et al. (2006)
[c] Smith (1994)
[d] Kirkby (2012)

16.6.2 Challenges in Recovery of Micronutrients

16.6.2.1 Non-effectiveness of Micronutrient Fertilizers

Fertilizers being a critical contribution to modern agriculture have made a significant contribution to the achievement of high yields of crops (Erisman et al. 2008). The productivity of agriculture is reported to increase in several regions that have witnessed the Green Revolution by the application of fertilizers but quality (in terms of elemental composition) remained a challange. The reason for this inclination can be described by these two factors: (1) Extensive usage of high yield varieties (Monasterio and Graham 2000) and (2) The nonstop removal of micronutrients from soil by crops and non-replenishment by fertilizers, especially in poor countries (Cakmak 2009). A higher application of micronutrient fertilizers proves costly and this can alter the chemistry of soil a lot but it can prove cost-effective in deficit situations, especially with the foliar application.

16.6.2.2 Soil Acidification (Acidic vs Alkaline Soils)

Soil acidification is a complex process which in unnecessary for acidic soils (Varma et al. 2017; Kumar et al. 2017a, b; Meena et al. 2017a) but much needed for alkaline soils for proper avalibility of nutrients (Brady and Weil 2013). The application of acidic treatments like farm manure, acidic biochar, reduced forms of S, acids (organic/inorganic), and application of S with S reducing bacteria can be important approaches in decreasing pH of alkaline soils.

16.6.2.3 Disturbance in Soil Structure

Soil structure applies significant effects to the environment and edaphic conditions. It can be expressed as a degree of aggregates stability. Aggregation is the result of rearrangement, flocculation, and cementation of particles. The stability of aggregates is generally used as an indicator of soil structure (Six et al. 2000). It is facilitated with ionic bridging, soil organic carbon, soil biota, carbonates, and clay concentration. Complex interactions of these aggregates are disruptive or problematic to aggregation. Compounds of organo-metals and cations form bridges between these particles. Plants, animals, microorganisms and their exudates are sources of soil organic carbon. The weakening in the structure of the soil is gradually seen as a form of degradation of soil (Chan et al. 2003) and is frequently related to the land usage and crop or soil or management practices. Soil structure also disturbs the retention and soil water movement, erosion, crusting, nutrient recycling, root penetration, and crop yield. Extensive contamination and manipulation of soil can interrupt the soil structure greatly thus disturbing the nutrients movement, soil biota, and soil physical properties (Brady and Weil 2013).

16.6.3 Managing the Recovery of Micronutrients

16.6.3.1 Chemical Measures

High contents of exchangeable sodium and low electrolyte concentration are major problems found in alkali (sodic) soils. Soil particles become isolated which leads to the low leaching conditions until the excess sodium exchange is done; this is due to the sodium effects with decreased concentration of ions. The most communal technique of replacement of exchangeable sodium is the addition of Ca^{2+} or sulfur, iron sulfate, aluminum sulfate to the soil and it dissolves the soil lime and releases some amount of calcium to the soil solution. Application of gypsum ($CaSO_4.2H_2O$) is considered as the easiest and common source of calcium. The existence of calcium chloride ($CaCl_2$) in the locality of chemical factories is also a source of calcium. Gypsum, limestone, and sulfur application to alkaline soil replace exchangeable sodium ions with Ca^{2+}; thus increasing the availability of the micronutrients in the soil. Gypsum is considered as the most abundant source of calcium to the alkaline soils; however, the existence of $CaCl_2$ in the soil is a good source of calcium too (Jafari et al. 2018).

16.6.3.2 Soil Management Measures

If interval management of marginally alkaline soils is not done, they may again convert into saline-sodic or sodic soils. Despite physical and chemical measures, recovery of micronutrients in alkaline soils can also be done by soil management. Different agronomic measures like irrigation management, reduced tillage, managing plant population, crop rotation, and soil fertility management efficiently according to the need for alkaline soil boost the micronutrient content in the soil (Brady and Weil 2013).

16.6.3.3 Green Manuring

The worth of green leguminous manure crops for improvement of soil fertility has been forecasted since early times (Yandvinder-Singh and Khind 1992). The key function of green manuring is the addition of organic matter to the soil. The benefits associated with green manuring include improvement in organic matter concentration, nutrients provision to improve the physical and microbiological properties of the soil. The most important part of the application of green manuring is that it supplies nutrients to plants. Green manuring improves the soil aeration, structure and adds nutrients and organic matter, which helps to control weeds, insects-pests and increases the soil's biodiversity by exciting the growth of beneficial microbes and other soil organisms (Meena et al. 2016, 2018). Green manuring changes the pH of the soil in two ways. Organic acids and CO_2 formed during the decay of green manure can supply protons to the soil by reducing the pH (Yandvinder-Singh and Khind 1992). However, some organic reducing elements formed during the decay of green manure can reduce Mn and Fe oxides causing a rise in soil pH because protons tend to reduce oxides. An increase in soil pH may also result in mineralization of organic anions to H_2O and CO_2, thus removing the H^+. Common crops used for green manuring like jantar (*Sesbania sesban*), sunnhemp (*Crotalaria juncea*), and berseem (*Trifolium alexandrinum*) serve usually on decomposition as sources of available nutrients besides substitute as solubilizing agents for Ca, thus neutralizing high pH of alkali soils and helps in management of micronutrients. Crops such as Indian clover (*Trifolium amoenum*) and cluster bean (*Cyamopsis tetragonoloba*) are also used for green manuring.

16.7 Enhancing the Bioavailability of Micronutrient in Alkaline Soils

Soil modulation and conditioning are mandatory to improve availability of micronutrient for plant uptake. Figure 16.3 has a general measure possible to intermingle for better availability of micronutrients for plant growth.

Fig. 16.3 Integrated approaches to improve the availability of micronutrients in alkaline soil

16.7.1 Modification of Rhizosphere pH

Soil pH is a measure of the activity of active H^+ present in the soil and is in dynamic equilibrium with a negatively charged solid phase. High pH ranges from pH 7 of calcareous soils to pH higher than 8 of alkaline saline soils (Qadir et al. 2007). Soils with high pH exhibit different nutritional constraints like the Na toxicity attached with excess HCO_3^-, deficiency of cationic micronutrients and mechanical impedance, water deficiency and poor aeration (Wilkinson et al. 2000). Chemical properties of soil in the rhizosphere are relatively different from those present in the bulk soil including soil pH away from the root's rhizosphere (Dotaniya and Meena 2015). If the soil is alkaline, lowering of soil pH could be done by using several products including iron sulfate, elemental sulfur, aluminum sulfate, organic mulches, and acidifying nitrogen. Rhizosphere pH can also be changed by using nitrogen source fertilizers as nitrogen disturbs the rhizosphere pH via several mechanisms such as the release or uptake of H^+ by roots of plants in reply to NO_3 and NH_4 uptake ratio, displacement of OH^- or H^+ adsorbed on solids and denitrification or nitrification reactions (Brady and Weil 2013).

16.7.2 Use of Soil Conditioners

Soil conditioners are different products that are added to soil to improve the soil's fertility, physical qualities, soil structure, and sometimes its mechanics. Soil conditioners are also used to rebuild soils and improve poor soils that are damaged by improper management of soil (Noble et al. 2011). A wide range of ingredients are being used as soil conditioners due to their ability to improve soil quality such as compost, hydro-absorbents, biochar, bone meal, polymers, compost tea, manure, vermiculite, peat, lime sphagnum moss, sulfur, and biosolids. The application of soil conditioners could help in improving the soil structure by binding all soil particles into large aggregates. Application of soil conditioners increases the number of pore space and increases water movement, nutrients, and air exchange in roots. Elemental sulfur or micro-fine sulfur is a soil conditioner to lower soil pH in alkaline soils and to enhance the availability of different micronutrients (Kumar et al. 2017a, b; Meena et al. 2019). The concentrated form of humus (potassium humate) is a naturally occurring lignite which is called brown coal. It could be used as a substitute for the use of synthetic soil polymers in the disaggregation of soil and amelioration of poor structure stability (Kumar et al. 2013).

16.7.3 Use of Biofertilizers

Biofertilizers contain microorganisms which readily promote the adequate supply of micronutrients to plants thus facilitating plant growth and development (Ghany et al. 2014). The use of biofertilizers is always eco-friendly and one of the best modern-age tools in agriculture being used to enhance the fertility and quality of the soil

(Jangir et al. 2016). The appropriate application of biofertilizers to soil accelerates different microbial processes to increase the bioavailability of micronutrients to the plants (Khosro and Yousef 2012). Biofertilizers are the important components of integrated nutrient management in soils while can playing a significant part in the sustainability and productivity of the soil (Rai 2006).

16.7.4 Microbe Containing Biofertilizers

Microorganisms are the basic tools in agriculture incapacitating the problems related to the unnecessary use of pesticides and different types of chemical fertilizers (Bashan et al. 2014). Microbial cultures and their products are now being commonly used in modern agriculture and near-future application of microbes is predicted to become a very common practice for enhancement and maintenance of soil fertility (Singh et al. 2011). The usage of microbes in the form of biofertilizers in agriculture is considered a substitute for various chemical fertilizers in agriculture due to their capability of enhancement of food safety and crop production (Rai 2006). Microbes including PGPR, fungi, and cyanobacteria have shown activities identical to biofertilizers in the agricultural sector (Mahanty et al. 2017). These microbe based biofertilizers play a crucial role in micronutrient mobilization, iron sequestration, phosphate solubilization, and fixation of N. Azola spp. and their metabolites are significantly involved in delivery of a nutrients like Zn, K, Fe, P, Mo, and other micronutrients (Ghany et al. 2014). In bacterial membrane, iron is reduced from Fe^{3+} to Fe^{2+} in gram-positive and gram-negative bacteria which is released in the cells from siderophores through gating mechanism which attaches together the outer and inner membranes. Siderophores participate as solubilizing agents for the Fe from mineral and organic compounds in Fe-limited conditions (Ahemad and Saghir Khan 2011).

16.7.5 Microbial Consortia

Use of microbial consortium for solublization of micronutrients is also a novel phenomenon which is widely being explored now a days. Screening of specific microbial community is first step which is followed by further enrichement and then innoculation of soil or plant seeds with screened consortium. Microbes used as innoculum for plants do various functions like, N fixcation and macro/micro nutrient solublizaion ultimately improving plant growth as reported in literature (Cunningham and Kuiack 1992; Rai 2006; Bahadur et al. 2014; Meena et al. 2017).

16.7.6 Factors Affecting Sustainability of Biofertilizers

16.7.6.1 Soil Fertility

Soil embodies a much diverse environment for microbes living in it as multiple amounts of the solid portions in the soil, i.e. organic matter, sand silt, and clay and delivers masses to the native microbes (Brady and Weil 2013).

16.7.6.2 Rhizosphere Management

Plant roots exhibit a close linkage with the variety of microbial colonies recruited from the soil with the help of root exuded carbon. Rhizosphere management is an important factor regarding the sustainability of biofertilizers (Brady and Weil 2013).

16.7.6.3 Soil Organic Matter

Soil organic matter comprises exudates from living roots, sloughed-off root cells, invertebrate and microbial biomass, dead roots polysaccharides, and fungal hyphae. Soil organic matter serves as a source of different carbon compounds which are essential to support the high levels of microbial activities (Brady and Weil 2013).

16.8 Conclusions

Plant nutrition and soil fertility incorporate the wise management of the soil environment to deliver the essential plant nutrients in the required amounts for the optimum performance of the plant. The availability of micronutrients to plant is purely linked with the soil environment and type of the parent material. Arid regions of the world mostly have alkaline soils that result in high availability B, while humid regions of the world have acidic soils that pose high availability of Mn, Zn, and Fe. Despite extensive resources and research, it is never easy to completely predict the behavior of micronutrients in the soil as it is highly dependent on different factors. As micronutrients are required in very fewer amounts, most soils have sufficient amounts to meet plant needs. However, the availability of micronutrients in the soil can be significantly increased by adopting several practices. The application of nutrients containing fertilizers, both organic and inorganic, is the broadly used technique across the world to increase the availability of micronutrients in alkaline soils. Adaptation of biological practices like the application of biofertilizers, soil conditioners, and nutrients solubilizing media can also contribute to enhancing the availability of micronutrients in alkaline soils; however, these practices should be adopted according to the soil nutrient management guidelines regarding crop types. The affordability of farmers to resources and availability of information should be the priorities while referring to these practices.

16.9 Future Perspectives

The availability of micronutrients in the soil is closely related to the environment and kind of parent materials where soils are developed. According to changes in soil conditions and nutrient requirement levels of plants, we can attempt to regulate the availability of micronutrients in soils by adopting some feasible and realistic approaches. Alkaline soils usually have high pH, free $CaCO_3$, and low organic matter. Subsequently, nutrients deficiency in alkaline soils is the most significant limiting factor for better crop yield, after moisture stress (Rashid et al. 2016). Many factors such as biological activity, pH, redox potential, soil organic matter, clay contents, and CEC are significant in defining the availability of micronutrients in alkaline soils (Brady and Weil 2013). Focusing on the increase in yield, one can suggest that the use of micronutrient-enriched fertilizers could increase micronutrient availability in alkaline soils. Root persuaded changes in the rhizosphere also disturb the transportation and micronutrient availability from rhizosphere to plant. Application of plant growth regulators and exogenous application of fertilizers can be employed to lessen the micronutrient losses and salt-induced losses. Root exudates are a mixture of different soluble organic substances. Minimizing the soil alkaline properties and enhancing micronutrient availability could be done by lowering soil pH by using several products including acidifying nitrogen, elemental sulfur, organic mulches, iron sulfate, and aluminum sulfate. If the soil is alkaline, lowering of soil pH could be done by using several products including elemental sulfur, iron sulfate, aluminum sulfate, acidifying nitrogen, and organic mulches.

The use of biofertilizers in agriculture always proves to be eco-friendly and undoubtedly, it is still one of the best methods in agriculture to improve the quality and fertility status of soils. The accurate application of biofertilizers to alkaline soil can accelerate the microbial process and thus enhance the availability of micronutrients. Alkaline soils are free drainage and highly porous in common. By adopting various soil management measures, we can maximize the availability of micronutrients in alkaline soils. Moreover, amending alkaline soils with different products and the organic product could help to lower the rhizosphere pH from alkaline to normal, thus increasing the availability of micronutrients. The use of soil conditioners can also help to build poor soil structure of alkaline soils by binding soil particles together to aggregate and help the movement of micronutrients in the soil to plant.

References

Abadía J, Vázquez S, Rellán-Álvarez R (2011) Towards a knowledge-based correction of iron chlorosis. Plant Physiol Biochem 49:471–482. https://doi.org/10.1016/j.plaphy.2011.01.026

Ahemad M, Saghir Khan M (2011) Assessment of plant growth promoting activities of Rhizobacterium *Pseudomonas putida* under insecticide-stress. Microbiol J 1:54–64

Ahmad MSA, Ashraf M (2012) Essential roles and hazardous effects of nickel in plants. In reviews of environmental contamination and toxicology. Springer, New York, pp 125–167

Ahmed N, Abid M, Ahmad F (2011) Impact of boron fertilization on dry matter production and mineral constitution of irrigated cotton. Pakistan J Bot 43:2903–2913

Al-Amery MM, Hamza JH, Fuller MP (2011) Effect of boron foliar application on reproductive growth of sunflower (*Helianthus annuus* L.). Int J Agron 2011:1–5. https://doi.org/10.1155/2011/230712

Alloway BJ (2009) Soil factors associated with zinc deficiency in crops and humans. Environ Geochem Health 31:537–548. https://doi.org/10.1007/s10653-009-9255-4

Bahadur I, Singh V, Kumar S (2014) Importance and application of potassic biofertilizer in Indian agriculture. Int Res J Biol Sci 3:80–85

Barker A, Pilbeam D (2015) Conclusion. In: Handbook of plant nutrition, 2nd edn. Taylor & Francis, Boca Raton, pp 725–730

Bashan Y, de-Bashan LE, Prabhu SR, Hernandez JP (2014) Advances in plant growth-promoting bacterial inoculant technology: formulations and practical perspectives (1998–2013). Plant and Soil 378:1–33. https://doi.org/10.1007/s11104-013-1956-x

Beauregard PB (2015) Not just sweet talkers: how roots stimulate their colonization by beneficial Bacteria. Adv Bot Res 75:1–20. https://doi.org/10.1016/bs.abr.2015.07.001

Bertini I, Rosato A (2007) From genes to metalloproteins: a bioinformatic approach. Eur J Inorg Chem 2007:2546–2555. https://doi.org/10.1002/ejic.200700186

Blasco B, Navarro-León E, Ruiz JM (2018) Oxidative stress in relation with micronutrient deficiency or toxicity. Plant Micronutr Use Effic 2018:181–194

Brady NC, Weil R (2013) Nature and properties of soils, the: Pearson new international edition. Pearson

Broadley M, Brown P, Cakmak I (2012) Function of nutrients. In: Marschner's mineral nutrition of higher plants. Academic Press, London, pp 191–248

Brundrett MC, Tedersoo L (2018) Evolutionary history of mycorrhizal symbioses and global host plant diversity. New Phytol 220:1108–1115. https://doi.org/10.1111/nph.14976

Bui VC, Franken P (2018) Acclimatization of *Rhizophagus irregularis* enhances Zn tolerance of the fungus and the mycorrhizal plant partner. Front Microbiol 9:1–13. https://doi.org/10.3389/fmicb.2018.03156

Cakmak I (2000) Tansley review no. 111: possible roles of zinc in protecting plant cells from damage by reactive oxygen species. New Phytol 146:185–205

Cakmak I (2009) Enrichment of fertilizers with zinc: an excellent investment for humanity and crop production in India. J Trace Elem Med Boroniol 23:281–289

Cakmak I, Torun B, Erenoğlu B (1998) Morphological and physiological differences in the response of cereals to zinc deficiency. Euphytica 100:349–357. https://doi.org/10.1007/978-94-011-4896-2_57

Carroll KC, Artiola JF, Brusseau ML (2006) Transport of molybdenum in a biosolid-amended alkaline soil. Chemosphere 65:778–785. https://doi.org/10.1016/j.chemosphere.2006.03.044

Cempel M, Nikel G (2006) Nickel: a review of its sources and environmental toxicology. Polish J Environ Stud 15:375–382

Chan KY, Heenan DP, So HB (2003) Sequestration of carbon and changes in soil quality under conservation tillage on light-textured soils in Australia: a review. Aust J Exp Agric 43:325–334

Chapman VJ, Edwards DG, Blamey FPC, Asher CJ (1997) Challenging the dogma of a narrow supply range between deficiency and toxicity of boron BT—boron in soils and plants: proceedings of the international symposium on boron in soils and plants held at Chiang Mai, Thailand, 7–11 September, 1997. In: Bell RW, Rerkasem B (eds). Springer, Dordrecht, pp 151–155

Chen W, He ZL, Yang XE et al (2010) Chlorine nutrition of higher plants: Progress and perspectives. J Plant Nutr 33:943–952. https://doi.org/10.1080/01904160903242417

Compant S, Clément C, Sessitsch A (2010) Plant growth-promoting bacteria in the rhizo- and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization. Soil Biol Biochem 42:669–678. https://doi.org/10.1016/j.soilbio.2009.11.024

Coogan TP, Latta DM, Snow ET, Max C, Lawrence A (2008) Toxicity and carcinogenicity of nickel compounds. CRC Crit Rev Toxicol 19(4):341–384

Cook CM, Kostidou A, Vardaka E, Lanaras T (1998) Effects of copper on the growth, photosynthesis and nutrient concentrations of Phaseolus plants. Photosynthetica 34:179–193

Cunningham JE, Kuiack C (1992) Production of citric and oxalic acids and solubilization of calcium phosphate by *Penicillium bilaii*. Appl Environ Microbiol 58:1451–1458

Dear BS, Weir RG (2004) Boron deficiency in pastures and field crops. Agfact P1.AC.1, NSW Agriculture, NSW

Degola F, Fattorini L, Bona E (2015) The symbiosis between *Nicotiana tabacum* and the endomycorrhizal fungus *Funneliformis mosseae* increases the plant glutathione level and decreases leaf cadmium and root arsenic contents. Plant Physiol Biochem 92:11–18. https://doi.org/10.1016/j.plaphy.2015.04.001

Dhaliwal SS, Naresh RK, Mandal A et al (2019) Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: a review. Environ Sustain Indic 1–2:100007. https://doi.org/10.1016/j.indic.2019.100007

Dimkpa CO, Bindraban PS (2016) Fortification of micronutrients for efficient agronomic production: a review. Agron Sustain Dev 36:1–26. https://doi.org/10.1007/s13593-015-0346-6

Dotaniya ML, Meena VD (2015) Rhizosphere effect on nutrient availability in soil and its uptake by plants: a review. Proc Natl Acad Sci India Sect B - Biol Sci 85:1–12. https://doi.org/10.1007/s40011-013-0297-0

Dučić T, Polle A (2005) Transport and detoxification of manganese and copper in plants. Boronrazilian J Plant Physiol 17:103–112. https://doi.org/10.1590/S1677-04202005000100009

Egamberdiyeva D (2007) The effect of plant growth promoting bacteria on growth and nutrient uptake of maize in two different soils. Appl Soil Ecol 36:184–189. https://doi.org/10.1016/j.apsoil.2007.02.005

Elham J, Ahmad G, Ghassem HB (2014) The effect of soil and foliar fertilization with iron on yield and leaf chemical composition of four spotted bean cultivars in a calcareous soil. Greener J Biol Sci 4:116–127. https://doi.org/10.15580/gjbs.2014.4.012714069

Erisman JW, Sutton MA, Galloway JN, Klimont Z, Winiwarter W (2008) How a century of ammonia synthesis changed the world. Nat Geosci 1:636–639. https://doi.org/10.1038/ngeo325

Fageria VD (2001) Nutrient interactions in crop plants. J Plant Nutr 24:1269–1290. https://doi.org/10.1081/PLN-100106981

Fageria NK, Baligar C, Clark RB (2002) Micronutrients in crop production. Adv Agron 77:185–268

Fan XH, Lin DX, Shen M, Qin SW (2005) Characteristics of mineralization and nitrification in the calcareous soils from a long-term fertilization experimental field. Acta Pedol Sin 42:340–343

Ferrol N, Tamayo E, Vargas P (2016) The heavy metal paradox in arbuscular mycorrhizas: from mechanisms to biotechnological applications. J Exp Bot 67:6253–6565. https://doi.org/10.1093/jxb/erw403

Field KJ, Pressel S, Duckett JG (2015) Symbiotic options for the conquest of land. Trends Ecol Evol 30:477–486. https://doi.org/10.1016/j.tree.2015.05.007

Fitter AH, Helgason T, Hodge A (2011) Nutritional exchanges in the arbuscular mycorrhizal symbiosis: implications for sustainable agriculture. Fungal Biol Rev 25:68–72

Frossad E, Bucher M, Machler F (2000) AGjDPG 3: Wissenschaftliches Publizieren (mit AGI). J Sci Food Agric 80:861–879

Ghany TMA, Alawlaqi MM, Abboud MAA (2014) Role of biofertilizers in agriculture: a brief review. Mycopathologia 11:95–101

Gheibi MN, Kholdebarin B, Malakouti MJ (2011) Effect of various nickel levels on growth and chlorophyll content of corn plants supplied with urea and ammonium nitrate. J Food Agric & Amp Environ 9:583–587

Goldman CR (2009) Micronutrient elements (Co, Mo, Mn, Zn, Cu). Encycl Inl Waters 2009:52–56. https://doi.org/10.1016/B978-012370626-3.00094-6

Graham RC (2004) Soil mineralogy with environmental applications. Vadose Zo J 3:724. https://doi.org/10.2136/vzj2004.0724

Greenwood NN, Earnshaw A (1984) Chemistry of the elements, vol 1. Pergamon Press, Oxford

Gupta UC, Wu K, Liang S (2008) Micronutrients in soils, crops, and livestock. Earth Sci Front 15:110–125. https://doi.org/10.1016/s1872-5791(09)60003-8

Hall JO (2018) Molybdenum. In: Veterinary toxicology. Academic Press, London, pp 463–467

Halvin JL, Beaton JD, Tisdale SL, Nelson WL (2005) Soil fertility and fertilizers: an introduction to nutrient management. Prentice Hall, New Jersey

Harasim P, Filipek T (2015) Nickel in the environment. J Elem 20:525–534. https://doi.org/10.5601/jelem.2014.19.3.651

Harmsen K, Vlek PLG (1985) The chemistry of micronutrients in soil. Ironrtil Res 7:1–42. https://doi.org/10.1007/BF01048994

Hasani M, Zamani Z, Savaghebi G, Fatahi R (2012) Effects of zinc and manganese as foliar spray on pomegranate yield, fruit quality and leaf minerals. J Soil Sci Plant Nutr 12:471–480. https://doi.org/10.4067/s0718-95162012005000009

Hosseini H, Khoshgoftarmanesh AH (2013) The effect of foliar application of nickel in the mineral form and urea-Ni complex on fresh weight and nitrogen metabolism of lettuce. Sci Hortic 164:178–182. https://doi.org/10.1016/j.scienta.2013.09.030

Jafari M, Tavili A, Panahi F (2018) Amendment of saline and alkaline soils. In: Environmental science and engineering. Springer, Cham, pp 167–174. https://doi.org/10.1007/978-3-319-54828-9_4

Jangir CK, Singh D, Kumar S (2016) Yield and economic response of biofertilizer and fertility levels on black gram (*Vigna mungo* L.). Prog Res – Int J 11:5252–5254

Jangir CK, Kumar S, Lakhran H, Meena RS (2017) Towards mitigating malnutrition in pulses through biofortification. Trend Bios 10(17):2999–3002

Jeffery JJ, Uren NC (1983) Copper and zinc species in the soil solution and the effects of soil pH. Aust J Soil Res 21:479–488. https://doi.org/10.1071/SR9830479

Johal GS, Huber DM (2009) Glyphosate effects on diseases of plants. Eur J Agron 31:144–152. https://doi.org/10.1016/j.eja.2009.04.004

Kabata-Pendias A (2004) Soil–plant transfer of trace elements—an environmental issue. Geoderma 122:143–149. https://doi.org/10.1016/j.geoderma.2004.01.004

Kaiser BN, Gridley KL, Brady JN (2005) The role of molybdenum in agricultural plant production. Ann Bot 96:745–754. https://doi.org/10.1093/aob/mci226

Khosro M, Yousef S (2012) Bacterial biofertilizers for sustainable crop production: a review. J Agric Bol Sci 7:307–316

Kirkby E (2012) Introduction, definition and classification of nutrients. In: Marschner's mineral nutrition of higher plants. Academic Press, London, pp 3–5

Kizilgoz I, Sakin E (2010) The effects of increased phosphorus application on shoot dry matter, shoot P and Zn concentrations in wheat (*Triticum durum* L.) and maize (*Zea mays* L.) grown in a calcareous soil. Afr J Biotechnol 9:5893–5896. https://doi.org/10.5897/AJB10.319

Koo BJ, Adriano DC, Bolan NS, Barton CD (2004) Root exudates and microorganisms. In: Encyclopedia of soils in the environment. Elsevier, Amsterdam, pp 421–428

Kot FS (2009) Boron sources, speciation and its potential impact on health. Rev Environ Sci Biotechnol 8:3–28. https://doi.org/10.1007/s11157-008-9140-0

Kot FS (2015) Boron in the environment. In: Boron separation processes. Elsevier, Amsterdam, pp 1–33

Kumar R, Mehrotra NK, Nautiyal BD (2009) Effect of copper on growth, yield and concentration of Fe, Mn, Zn and cu in wheat plants (*Triticum aestivum* L.). J Environ Biol 30:485–488

Kumar D, Singh AP, Raha P (2013) Potassium humate: a potential soil conditioner and plant growth promoter. Int J Agric Environ Biotechnol 6:441. https://doi.org/10.5958/j.2230-732x.6.3.015

Kumar S, Meena RS, Pandey A, Seema (2017a) Soil acidity management and an economics response of lime and sulfur on sesame in an alley cropping system. Int J Curr Microb Applied Sci 6(3):2566–2573

Kumar S, Meena RS, Yadav GS, Pandey A (2017b) Response of sesame (*Sesamum indicum* L.) to Sulphur and lime application under soil acidity. Int J Plant Soil Sci 14(4):1–9

Lemanceau P, Expert D, Gaymard F (2009) Role of iron in plant–microbe interactions. Adv Boronot Res 51:491–549

Li BY, Zhou DM, Cang L (2007) Soil micronutrient availability to crops as affected by long-term inorganic and organic fertilizer applications. Soil Tillage Res 96:166–173. https://doi.org/10.1016/j.still.2007.05.005

Linderman RG (1997) Vesicular-arbuscular mycorrhizal (VAM) fungi. In: Plant relationships part B. Springer, Berlin Heidelberg, pp 117–128

López-Bucio J, Guevara-García A, Ramírez-Rodríguez V (2000) Agriculture for marginal lands: transgenic plants towards the third millennium. Dev Plant Genet Breed 5:159–165. https://doi.org/10.1016/S0168-7972(00)80025-0

Magnitskiy S (2011) Nickel the last of the essential micronutrients. Agron Colomb 29:49–56

Mahanty T, Bhattacharjee S, Goswami M (2017) Biofertilizers: a potential approach for sustainable agriculture development. Environ Sci Pollut Res 24:3315–3335. https://doi.org/10.1007/s11356-016-8104-0

Malakouti MJ (2008) The effect of micronutrients in ensuring efficient use of macronutrients. Turkish J Agric for 32:215–220. https://doi.org/10.3906/tar-0801-41

Marschner H (1995) Functions of mineral nutrients. In: Marschner's mineral nutrition of higher plants. Academic Press, London, pp 313–404. https://doi.org/10.1016/b978-012473542-2/50011-0

Masunaga T, Marques Fong JD (2018) In: Hossain MA, Kamiya T, Burritt DJ et al (eds) Strategies for increasing micronutrient availability in soil for plant uptake. Academic Press, London, pp 195–208

McGrath JM, Spargo J, Penn CJ (2014) Soil fertility and plant nutrition. Encycl Agric Food Syst 5:166–184. https://doi.org/10.1016/B978-0-444-52512-3.00249-7

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena VS, Mishra PK, Bisht JK, Pattanayak A (2017) Agriculturally important microbes for sustainable agriculture: volume 2: applications in crop production and protection. Springer, Singapore

Meena RS, Kumar S, Pandey A (2017a) Response of sulfur and lime levels on productivity, nutrient content and uptake of sesame under guava (*Psidium guajava* L.) based Agri-horti system in an acidic soil of eastern Uttar Pradesh, India. J Crop Weed 13(2):222–227

Meena BL, Fagodiya RK, Parjapat K, Kaledhonkar MJ, Sharma PC, Meena RS, Mitran T, Kumar S (2018) Legume green manuring: an option for soil sustainability. In: Meena RS, Das A, Lal R (eds) Legumes for soil health and sustainable management. Springer, Singapore, pp 387–408. https://doi.org/10.1007/978-981-13-0253-4_12

Meena RS, Kumar S, Bohra JS, Lal R, Yadav GS, Pandey A (2019) Response of alley cropping-grown sesame to lime and Sulphur on yield and available nutrient status in an acidic soil of eastern India. Energ Ecol Environ 4:65–74. https://doi.org/10.1007/s40974-019-00113-w

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020) Impact of agrochemicals on soil microbiota and management: a review. Landarzt 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020a) Long term impacts of topsoil depthand amendments on soil physical and hydrological properties of anAlfisol in Central Ohio, USA. Geoderma 363:1141164

Mendes R, Kruijt M, De Bruijn I (2011) Deciphering the rhizosphere microbiome for disease-suppressive bacteria. Science 80(332):1097–1100. https://doi.org/10.1126/science.1203980

Migocka M, Malas K (2018) In: Hossain MA, Kamiya T, Burritt DJ et al (eds) Plant responses to copper: molecular and regulatory mechanisms of copper uptake, distribution and accumulation in plants. Academic Press, London, pp 71–86

Millaleo R, Reyes-Díaz M, Ivanov AG (2010) Manganese as essential and toxic element for plants: transport, accumulation and resistance mechanisms. J Soil Sci Plant Nutr 10:476–494. https://doi.org/10.4067/s0718-95162010000200008

Miransari M (2013) Soil microbes and the availability of soil nutrients. Acta Physiol Plant 35:3075–3084. https://doi.org/10.1007/s11738-013-1338-2

Monasterio I, Graham RD (2000) Breeding for trace minerals in wheat. Food Nutr Bull 21:392–396. https://doi.org/10.1177/156482650002100409

Montalvo D, Degryse F, da Silva RC et al (2016) Agronomic effectiveness of zinc sources as micronutrient fertilizer. Adv Agron 139:215–267

Mulrooney SB, Hausinger RP (2003) Nickel uptake and utilization by microorganisms. Iron MS Microbiol Rev 27:239–261. https://doi.org/10.1016/S0168-6445(03)00042-1

Muntean D (2009) Boron, the overlooked essential element. Soil and Plant Laboratory, Bellevue, WA

Muthukumararaja T, Sriramachandrasekharan MV (2012) Critical limit of zinc for rice soils of Veeranam command area, Tamilnadu. India J Agric Biol Sci 7:23–34

Nable RO, Bañuelos GS, Paull JG (1997) Boron toxicity. Plant and Soil 193:181–198

Nakandalage N, Seneweera S (2018) In: Hossain MA, Kamiya T, Burritt DJ et al (eds) Micronutrients use efficiency of crop-plants under changing climate. Academic Press, London, pp 209–224

Nazif W, Perveen S, Saleem I (2006) Status of micronutrients in soils of district Bhimber (Jammu and Kashmir). J Agric Biol Sci 1:35–40

NFDC (1998) Micronutrients in agriculture. Pakistan Perspective Publication No. 4/98. Islamabad

Noble R (2011) Risks and benefits of soil amendment with composts in relation to plant pathogens. Australas Plant Pathol 40(2):157–167

Podleśna A (2012) Effect of fertilization on content and uptake of chlorine by oilseed rape under pot experiment conditions. J Elem 14:4. https://doi.org/10.5601/jelem.2009.14.4.773-778

Printz B, Lutts S, Hausman JF, Sergeant K (2016) Copper trafficking in plants and its implication on cell wall dynamics. Front Plant Sci 7:1–16. https://doi.org/10.3389/fpls.2016.00601

Priyanka N, Geetha N, Ghorbanpour M, Venkatachalam P (2019) Role of engineered zinc and copper oxide nanoparticles in promoting plant growth and yield: present status and future prospects. Academic Press, London, pp 183–201

Qadir M, Oster JD, Schubert S (2007) Phytoremediation of sodic and saline-sodic soils. Adv Agron 96:197–247. https://doi.org/10.1016/S0065-2113(07)96006-X

Rai M (ed) (2006) Handbook of microbial biofertilizers. CRC Press, Boca Raton, FL

Rashid A, Ryan J (2004) Micronutrient constraints to crop production in soils with Mediterranean-type characteristics: a review. J Plant Nutr 27:959–975. https://doi.org/10.1081/PLN-120037530

Rashid MI, Mujawar LH, Shahzad T (2016) Bacteria and fungi can contribute to nutrients bioavailability and aggregate formation in degraded soils. Microbiol Res 183:26–41. https://doi.org/10.1016/j.micres.2015.11.007

Raven JA (2017) Chloride: essential micronutrient and multifunctional beneficial ion. J Exp Bot 68:359–367. https://doi.org/10.1093/jxb/erw421

Rengel Z (2000) Manganese uptake and transport in plants. Met Ions Biol Syst 37:57–87. https://doi.org/10.1201/9781482289893-13

Riedel GF (2008) Copper production and usage chemistry of copper. In: Ecotoxicology. Elsevier, Amsterdam, pp 778–783

Rout GR, Sahoo S (2015) Role of iron in plant growth and metabolism. Rev Agric Sci 3:1–24. https://doi.org/10.7831/ras.3.1

Rutkowska B, Szulc W, Sosulski T, Stepień W (2014) Soil micronutrient availability to crops affected by long-term inorganic and organic fertilizer applications. Plant Soil Environ 60:198–203. https://doi.org/10.17221/914/2013-pse

Ruytinx J, Kafle A, Usman M (2019) Micronutrient transport in mycorrhizal symbiosis; zinc steals the show. Fungal Biol Rev 34:1–9. https://doi.org/10.1016/j.fbr.2019.09.001

Sağlam A, Yetişsin F, Demiralay M, Terzi R (2016) Copper stress and responses in plants. Elsevier, Amsterdam, pp 21–40

Sandstead HH (2015) Zinc. In: Handbook on the toxicology of metals, vol 1, 4th edn. Academic Press, London, pp 1369–1385. https://doi.org/10.1016/B978-0-444-59453-2.00061-5

Setia R (2004) Effect of continuous cropping and long-term differential fertilization on profile stratification of DTPA-extractable micronutrients. J Food Agric Environ 2:260–265

Sharma BD, Harsh-Arora R-K, Nayyar VK (2004) Relationships between soil characteristics and total and DTPA-extractable micronutrients in inceptisols of Punjab. Commun Soil Sci Plant Anal 35:799–818. https://doi.org/10.1081/CSS-120030359

Sheykhbaglou R, Sedghi M, Shishevan MT, Sharifi RS (2010) Effects of nano-iron oxide particles on agronomic traits of soybean. Not Sci Biol 2:112–113. https://doi.org/10.15835/nsb224667

Shier WT (1994) Metals as toxins in plants. Toxin Rev 13:205–216. https://doi.org/10.3109/15569549409089960

Siedow JN (1991) Plant lipoxygenase: structure and function. Annu Rev Plant Physiol Plant Mol Biol 42:145–188. https://doi.org/10.1146/annurev.pp.42.060191.001045

da Silveira VC, Fadanelli C, Sperotto RA (2009) Role of ferritin in the rice tolerance to iron overload. Sci Agric 66:549–555. https://doi.org/10.1590/s0103-90162009000400019

Singh A, Parmar N, Kuhad RC, Ward OP (2011) In: Singh A, Parmar N, Kuhad RC (eds) Bioaugmentation, biostimulation, and biocontrol in soil biology BT—bioaugmentation, biostimulation and biocontrol. Springer, Berlin, Heidelberg, pp 1–23

Sirko A, Polonica RB-AB (2000) Plant ureases: roles and regulation. europepmc.org

Six J, Elliott ET, Paustian K (2000) Soil structure and soil organic matter: II. A normalized stability index and the effect of mineralogy. Soil Sci Soc Am J 64:1042–1049. https://doi.org/10.2136/sssaj2000.6431042x

Smith SR (1994) Effect of soil pH on availability to crops of metals in sewage sludge-treated soils. I. Nickelckel, copper and zinc uptake and toxicity to ryegrass. Environ Pollut 85:321–327. https://doi.org/10.1016/0269-7491(94)90054-X

Sun XH, Yu G, Li JT (2014) A heavy metal-associated protein (AcHMA1) from the halophyte, *Atriplex canescens* (Pursh) nutt., confers tolerance to iron and other abiotic stresses when expressed in Saccharomyces Cerevisiae. Int J Mol Sci 15:14891–14906. https://doi.org/10.3390/ijms150814891

Tabatabai MA, Sparks DL, Shuman LM (2005) Chemistry of micronutrients in soils. Soil Science Society of America, Madison

Taiz L, Zeiger E (2006) Plant physiology. Sinauer Associates, Sunderland

Tallkvist J, Oskarsson A (2015) Molybdenum. In: Handbook on the toxicology of metals. Academic Press, London, pp 1077–1089

Vance GF (2005) Soil and water chemistry: an integrated approach. Vadose Zo J 4:445. https://doi.org/10.2136/vzj2004.0002br

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan region, India. Int Chem Studies 5 (4):1558–1560

Vinit-Dunand F, Epron D, Alaoui-Sossé B, Badot PM (2002) Effects of copper on growth and on photosynthesis of mature and expanding leaves in cucumber plants. Plant Sci 163:53–58. https://doi.org/10.1016/S0168-9452(02)00060-2

Watmough SA, Eimers MC, Dillon PJ (2007) Manganese cycling in Central Ontario forests: response to soil acidification. Appl Geochem 22:1241–1247. https://doi.org/10.1016/j.apgeochem.2007.03.039

Watts-Williams SJ, Patti AF, Cavagnaro TR (2013) Arbuscular mycorrhizas are beneficial under both deficient and toxic soil zinc conditions. Plant and Soil 371:299–312. https://doi.org/10.1007/s11104-013-1670-8

Watts-Williams SJ, Smith FA, McLaughlin MJ (2015) How important is the mycorrhizal pathway for plant Zn uptake? Plant and Soil 390:157–166. https://doi.org/10.1007/s11104-014-2374-4

Weggler K, McLaughlin MJ, Graham RD (2004) Effect of chloride in soil solution on the plant availability of biosolid-borne cadmium. J Environ Qual 33:496–504. https://doi.org/10.2134/jeq2004.4960

White PJ, Broadley MR (2001) Chloride in soils and its uptake and movement within the plant: a review. Ann Bot 88:967–988. https://doi.org/10.1006/anbo.2001.1540

White JG, Zasoski RJ (1999) Mapping soil micronutrients. Crop Res 60:11–26. https://doi.org/10.1016/S0378-4290(98)00130-0

Wilkinson R, Baligar V, Clark R (2000) Acidic and alkaline soil constraints on plant mineral nutrition. In: Plant-environment interactions. CRC Press, London, pp 146–190

Williams RJP, Fraústo da Silva JJR (2002) The involvement of molybdenum in life. Boroniochem Biophys Res Commun 292:293–299. https://doi.org/10.1006/bbrc.2002.6518

Yandvinder-Singh B-S, Khind CS (1992) Nutrient transformations in soils amended with green manures BT—advances in soil science: volume 20. In: Stewart BA (ed) Springer. NY, New York, pp 237–309

Yin Y, Impellitteri CA, You S-J, Allen HE (2002) The importance of organic matter distribution and extract soil:solution ratio on the desorption of heavy metals from soils. Sci Total Environ 287(1–2):107–119

Zanão Júnior LA, Fontes RLF, Neves JCL (2010) Rice grown in nutrient solution with doses of manganese and silicon. Rev Bras Ciência do Solo 34:1629–1639. https://doi.org/10.1590/s0100-06832010000500016

Zhuang X, Chen J, Shim H, Bai Z (2007) New advances in plant growth-promoting rhizobacteria for bioremediation. Environ Int 33:406–413. https://doi.org/10.1016/j.envint.2006.12.005

Biofortification of Cereals with Zinc and Iron: Recent Advances and Future Perspectives

17

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Abstract

Malnutrition like hunger, deficiency of essential nutrients, and obesity is affecting more than 2 billion people worldwide. In mineral malnutrition, iron (Fe) and zinc (Zn) deficiency affect a very large portion of the global population. The deficiency of Fe is responsible for the initiation of anemia as Fe is the main part of hemoglobin, while Zn deficiency causes decreased immunity and retarded growth in humans. Keeping in mind the worldwide issue of Fe and Zn malnutrition, various practices are being proposed to add these minerals to human food. In this regard, biofortification is an attractive approach, and cereals being global staple food, if fortified, can significantly compensate for this issue. Cereal biofortification with Fe and Zn can be done *via* agronomic practices, breeding for efficient accumulators, and chemical fortification of cereal grains. Agronomic biofortification in this regard is the most efficient and acceptable approach, in which we grow cereals with significant availability of Fe and Zn, so that these metals can accumulate in edible portions of crops. Besides this, genetically engineered crops derived from biotechnology, conventional breeding, and artificial fortification are some other possible options being opted to cope with this issue. In recent advances, the use of soil conditioners and the application of various soil amendments have gained a pace to ensure a consistent supply of Fe and Zn to crop plants for insuring significant fortification. Among these amendments, biofertilizers containing Fe and Zn solubilizing bacteria or bacterial metabolites, and exogenous application of Fe and Zn compounds are most prominent. Though a wide range of Fe and Zn fortified food products are available in the market along with derived supplements, but cereal's biofortification is the most economical and practical technique for the developing world. This chapter is an effort to discuss in detail, the worldwide issue of Fe and Zn deficiency coupled with the role of biofortification of Fe and Zn to counter this issue.

Keywords

Biofortification · Cereals · Zinc deficiency · Iron deficiency · Inorganic fertilizers

Abbreviations

C	Carbon
Ca	Calcium
DNA	Deoxyribonucleic acid
Fe	Iron
Fe-EDTA	Iron-Ethylene diamine tetra acetic acid

H	Hydrogen
K	Potassium
Mg	Magnesium
mg	Milligram
N	Nitrogen
O	Oxygen
P	Phosphorus
PGPR	Plant growth promoting rhizobacteria
ppm	Parts per million
RDA	Recommended daily intake
RNA	Ribonucleic acid
ROS	Reactive oxygen species
S	Sulfur
WHO	World Health Organization
Zn	Zinc

17.1 Introduction

The world is about to face immense pressure on its resources due to an exponential increase in the world population which is expected to be 9.7 billion by 2050 and 11 billion by 2100 (United Nations News 2019). Aiming to this immense population pressure, food insecurity and mall-nourishment have become an unprecedented challenge for humankind (Müller and Krawinkel 2005; UNICEF 2018; WHO 2018). Food insecurity triggered malnutrition is expected to affect almost 3 billion people worldwide (Carvalho and Vasconcelos 2013; Hoekenga 2014). Characterized by many types, malnutrition has a vast span of problems ranging from protein-energy to micronutrients deficiency having both short- and long-term effects in humans. Malnutrition widely termed as “Hidden Hunger” can cause the risk of various infections and nutritional diseases and disorders (WHO 2000). Many people have limited access to nutritious food contributing to mineral malnutrition (Welch and Graham 2004) among which (Fe), zinc (Zn), and other micronutrients have caused serious deficiencies in more than 2 billion people globally (WHO 2016; Black 2003a, b; Black et al. 2008). About 805 million people are not able to lead a healthy life due to hunger in developing countries and ~13.5% of the world population is lacking in daily calorie intake (McGuire 2013).

Cereals contribute to the largest portion of the general diet of people all over the world, and at the same time, the poor mineral composition (Fe and Zn) of cereals can lead to severe mineral deficiencies (Cakmak et al. 2010; Sperotto et al. 2012). Among various minerals, iron deficiency is the major nutritional disorder in the world as 1.6 billion people are suffering from Fe deficiency, leading to the widespread extent of anemia (De Benoist et al. 2008). Major outcomes of anemia are fatigue, low productivity, impaired physical growth, decreased mental development, increased risk of mortality, and less psychomotor development (Bothwell and Macphail 2004). On the other hand, World Health Organization has reported that

Zn is the fifth biggest risk factor in developing countries and ranked 11th at the global level (WHO 2002). Health problems caused by Zn deficiency include retarded mental growth, delayed wounds healing, diarrhea, weak immunity and reproductive capability, retarded cell growth, and many other diseases (Caulfield 2004).

To combat with the Fe and Zn deficiencies, different strategies have been used in developing countries (Pfeiffer and McClafferty 2007), out of which biofortification is considered to be the most useful one (Zhao and McGrath 2009). Among cereals, biofortification of rice (*Oryza sativa* L.), wheat, maize, common beans, and other staple food products are important (Aciksoz et al. 2011).

17.2 Biofortification and Its Urgency in Human Nutrition

The process of increasing the concentration of nutrients in the food crops using different strategies like agronomic or genetic approach is known as biofortification (White and Broadley 2005a, b; Jangir et al. 2017). Cereal crops are used as a staple food by major population so the biofortification of cereal crops is considered an effective strategy to combat mineral malnutrition.

Malnutrition is an actual issue and every third person in the world is suffering from it mainly caused by micronutrient deficiency. Among all deficient micronutrients, Fe and Zn are the most important micronutrients needed by a human. An estimated count of two billion people in almost 100 developing countries is facing severe micronutrient deficiency leading to blindness, mental illness, and even deaths (Iyengar and Nair 2000). The World Health Organization has stated that a large portion of the world population is suffering from Fe deficiency making them prone to anemia (WHO 2008). The countries facing high frequency of Fe and Zn deficiency symptoms consume cereals as staple food products which predict that poor nutrient composition of cereals is a leading cause (Cakmak et al. 2010; Bouis et al. 2011). In developing countries, wheat is the major staple food crop contributing up to 28% of dry matter production and 60% of the daily energy intake (Wang et al. 2011) and poor minerals containing wheat grains can be a cause of malnutrition.

Zinc plays an important role in reproduction, physical growth, immunity, diabetes control, digestion, and early healing of wounds. According to some estimates, 17.3% of the world population is severely affected by Zn malnutrition (Wessells and Brown 2012). While iron deficiency causes impaired mental and physical growth in adults. Fe deficiency is the biggest contributor to anemia, and it is so severe that it is responsible for 46,000 disabilities only in 2010 (Murray and Lopez 2013).

Biofortification is the most feasible technique to fight against hidden hunger and malnutrition. It is a combination of best traditional practices and modern biotechnology to produce micronutrient-rich staple food crops such as wheat, rice, maize, and millet (Mayer et al. 2008; Bouis et al. 2011). It is ranked as the third most effective strategy in fighting hidden hunger in the Copenhagen consensus done in 2008 (Gomez-Galera et al. 2010).

17.3 Role of Zinc and Iron in Plants and Human

The essential micronutrients needed by plants include Fe, Zn, Mn, Cu, Co, B, Cl, and Mo (Fageria et al. 2002), whereas Ni is recently added in the essential micronutrient list. Unlike macronutrients, plants require micronutrients in small amounts, but they play a very crucial role in plant growth and functions just like macronutrients (Fageria and Stone 2008). Iron is involved in many important processes in plants that include DNA replication, reactive oxygen species (ROS) generation, chlorophyll biosynthesis, electron transport chain, and nitrogen fixation (Nouet et al. 2011; Yruela 2013) (Fig. 17.1). Various metabolic processes taking place in mitochondria and chloroplast involve Fe as a cofactor (Fukao et al. 2011). Due to Fe deficiency, young plant leaves are susceptible to chlorosis (Marschner 1995). Likewise, Zn also performs very important cellular functions in the plant system as Zn is an important component of proteins (enzymes) (Fig. 17.2). Zinc is involved in the proper functioning of genetic material and affects the stability of DNA and RNA structures. It also plays a role in the synthesis of starch (Brown et al. 1993). Zinc-deficient plants show less activity of starch synthetase and less starch content as well (Jyung et al. 1975).

Iron and zinc play a major role in regulating enzyme functions involved in the metabolic pathways of the human body as well. They are crucial elements in the synthesis of organic compounds inside the human body, i.e. carbohydrates, proteins, vitamins, and fats. The daily intake requirement of Fe ranges between 8 and 18 mg per day depending upon the age and gender of the person, whereas it is 30 mg per day recommended for a pregnant female (Aciksoz et al. 2011; Bhullar and Gruissem 2013). Moreover, the daily intake recommendation for Zn ranges between 7 mg per day (UK Reference Nutrient Intake) and 11 mg per day (US Recommended Daily Allowance) (García-Bañuelos et al. 2014). Intake of Fe and Zn below these values can slow down the physiological activities of the adult body. In the human body, Fe is present in myoglobin, hemoglobin, cytochromes, and Fe-containing enzymes. Iron is stored in the liver in the form of ferritin and hemosiderin (Conrad et al. 1999). It is involved in various complex processes like oxygen transport, where it acts as a prosthetic group in myoglobin and hemoglobin protein carriers in the human body. It can convert blood sugar into energy that is required by the body to perform important body functions (García-Bañuelos et al. 2014). The World Health Organization has reported that Fe deficiency prevails more among women and children. Approximately 91% of females of age ranging from 16 to 64 years do not take recommended daily intake (RDA) of iron and 6% women are suffering from anemia (Henderson et al. 2003).

Similarly, zinc is also required for the proper functioning of the immune system and it also helps in cell growth and division. Zinc supplements can be used for the treatment of diarrhea, malaria, and pneumonia (Sazawal et al. 2001). They are also given to children for their growth improvement and reduction in child mortality rate. At present, about 30% of the World's population is facing Zn related issues (Lowe et al. 2009; Yakoob et al. 2011). Subnormal reproductive function and reduced immune competence and growth are the important negative impacts of Zn deficiency

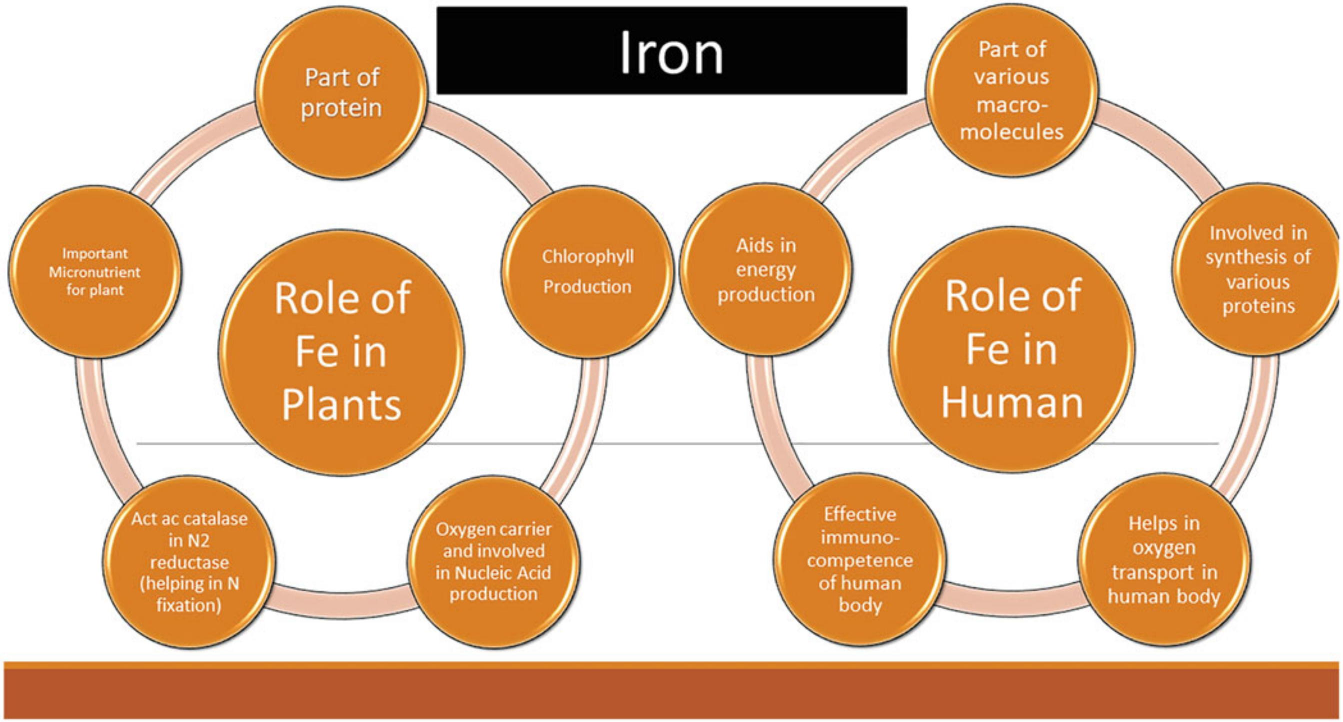

Fig. 17.1 Role of iron in plants and human

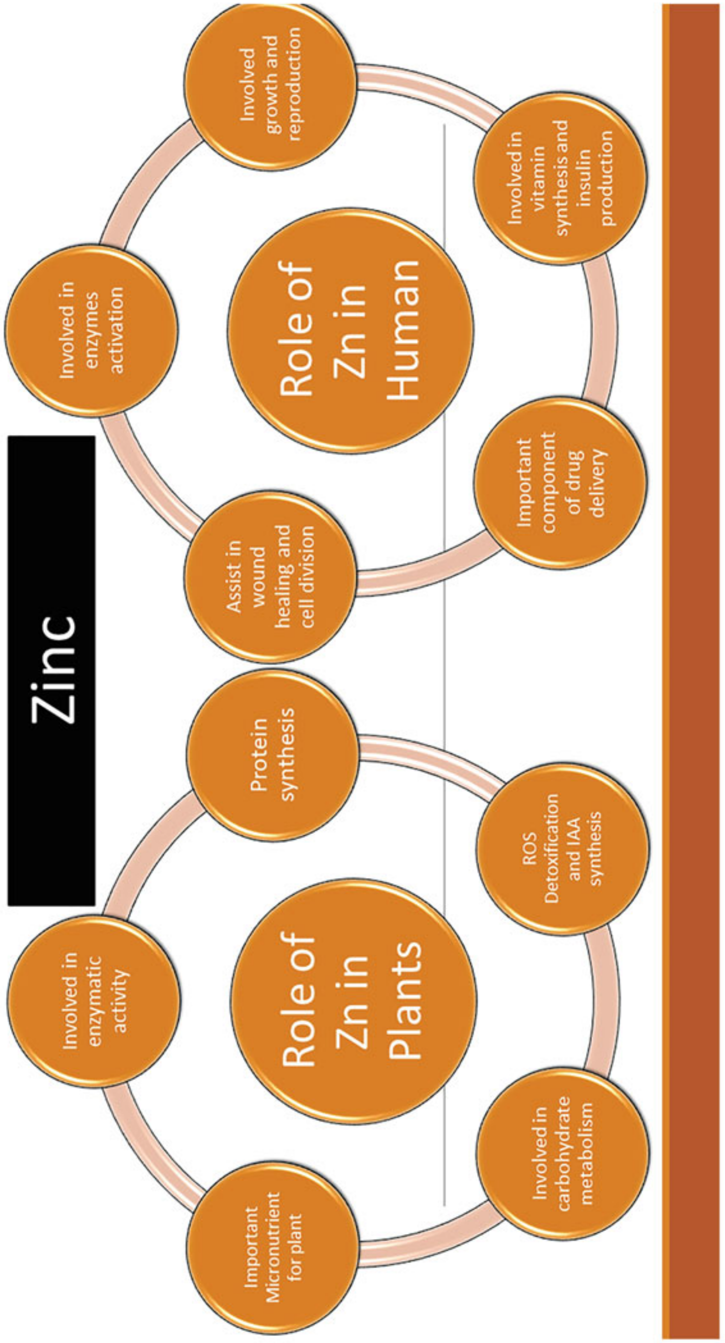

Fig. 17.2 Role of zinc in plants and human

(García-Bañuelos et al. 2014). Dermatitis, disturbance in neurological behavior during infancy, anorexia, skin changes, growth retardation, impaired taste acuity, and recurrent infections are the major health issues common in children. Among adolescents, abnormal skeletal growth and late sexual maturation are common, whereas in adults and elderly persons, late or no healing of chronic leg ulcers and various infections are common problems caused by Zn deficiency (Tesan et al. 2011; Gibson 2012).

17.4 Methods of Biofortification

According to International Biofortification Research and Development, biofortification is a natural and long-lasting procedure to cure malnutrition in both plants and animals. It is sustainable and cost-effective especially for under-developed populations (Bouis 2003). Biofortification works by increasing the micronutrient content of crops using different techniques, i.e. agronomic biofortification, conventional breeding, and genetic engineering technique (Khush et al. 2012) (Fig. 17.3).

17.4.1 Agronomic Biofortification

Agronomic biofortification is also named as mineral fertilization. In this technique, fertilizers rich in nutrients are applied to plants and soil to increase the micronutrient concentration in the edible portion of plants (Carvalho and Vasconcelos 2013). It is a simple and immediate method to overcome the mineral deficiency problem. Mineral elements are present in the soil in many ways like adsorbed ions, free ions, precipitates, or in the form of dissolved compounds and may get exhausted if the net flux is negative (White and Broadley 2009). One drawback of our soils is the decreased bioavailability of mineral elements, therefore, when the crops are grown in mineral deficient soils, the application of nutrient fertilizers becomes mandatory. Agronomic biofortification also aims to improve the mobilization and solubility of nutrients in the soil. There are several soil factors involved in the success rate of this biofortification technique, i.e. mobilization of minerals in plants and soil, the composition of the soil, and the accumulation site of minerals (Zhu et al. 2007; Hirschi 2009).

The agronomic biofortification technique is considered a universal solution as it is being practiced for many nutrients' incorporation in our food. So far, good results have been achieved with selenium (Se), iodine (I), and Zn because of their good mobility in soil. However, Fe has very low mobility in the phloem as well as in soil. Therefore, direct application of Fe fertilizers is not effective for plants because Fe becomes adsorbed or precipitated in the soil which makes it immobile and unavailable to plants. Iron-chelates have proven to be a good alternative to Fe-fortified fertilizers (Shuman 2017; Meena et al. 2020b). Agronomic biofortification of Zn in rice genotype has been proven to be a very beneficial approach. In this approach, Zn

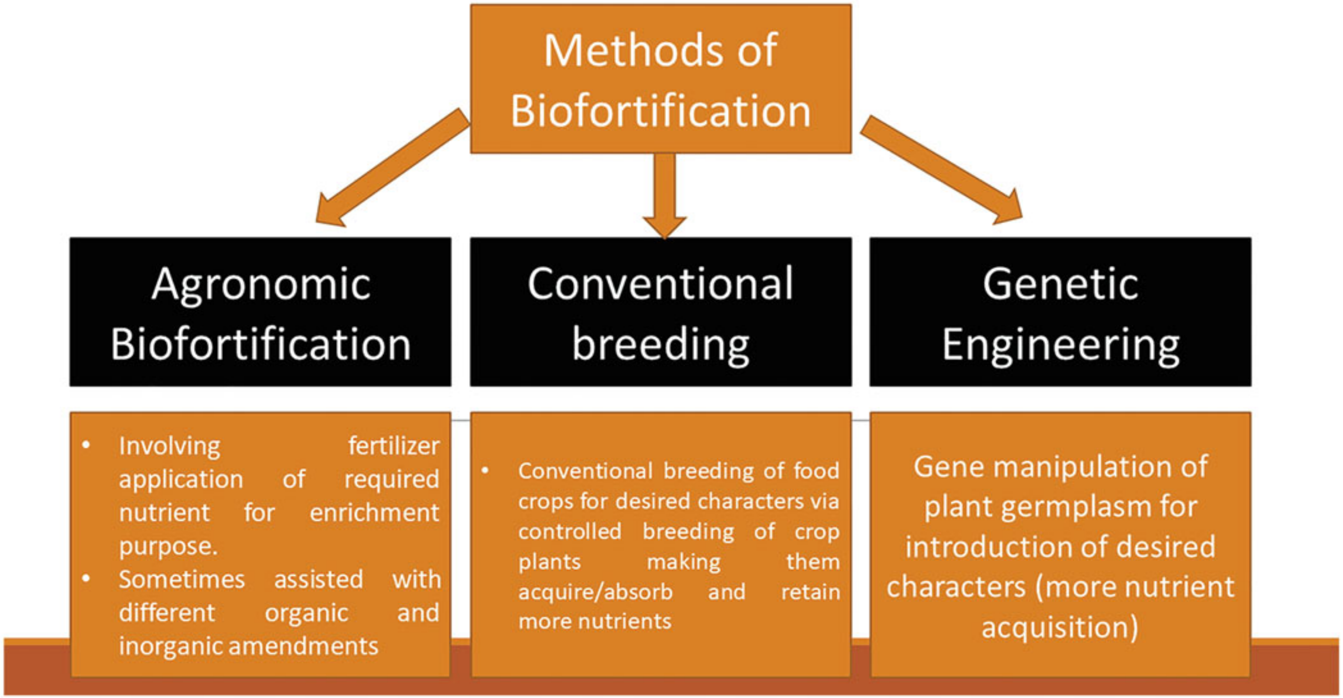

Fig. 17.3 Methods of biofortification

uptake by roots as well as its transport to grains during the reproductive stage increases under the influence of applied Zn fertilizer (Shivay et al. 2008a, b).

17.4.1.1 Zinc Biofortification in Cereals

Enrichment of cereal grains with the required ingredients during their growth is referred to as agronomic biofortification (Cakmak 2008, b). These cereal crops are then harvested and made a part of the food chain as a biofortified diet for the community. This process has been proved to be the most useful for the eradication of Zn deficiency from the population instead of using Zn supplements. Out of various Zn application methods, soil and foliar application are considered useful to achieve significant influx of Zn into edible plant tissues. With different limitations of various methods analyzed, soil application of Zn for biofortification in crops is a significantly useful approach (Liu et al. 2016). Application of Zn in the soil as a fertilizer can be done in the form of Zn compounds like zinc nitrate [$Zn(NO_3)_2$], zinc chloride ($ZnCl_2$), zinc oxide (ZnO), zinc sulfate ($ZnSO_4$), zinc-coated urea, and zinc oxy-sulfate. Before the sowing of wheat, the application of $ZnSO_4$ to the soil is a common practice to alleviate Zn deficiency (Cakmak 2008, b).

Zinc fertilizer application for agronomic biofortification of Zn has provided good responses for several staple cereal crops especially rice and wheat (Katyal and Rattan 2003). As a source of Zn, Shivay et al. (2008a, b) have concluded that Zn-coated urea, when applied in wheat-rice cropping pattern, found to be very effective in terms of Zn fortification in grains (Shivay et al. 2008a, b). It can be a practical strategy for eradication of Zn-malnutrition. Various projects have been run to ensure Zn fertilizer supplementation in agro-ecosystem to acquire this purpose. A fertilizer project named “Harvest Zinc” was conducted by “Harvest Plus” program in 2008 that was aimed at checking Zn fertilizer effect in improving Zn concentration in staple cereal food crops including wheat and rice in almost seven countries that include China, India, Thailand, Pakistan, Turkey, Zambia, and Brazil (Cakmak 2012). Table 17.1. Following the table shows some studies regarding Zn fortification in various crops under the application of various forms of Zn sources in different crops to make them Zn fortified Zn sources (Table 17.1).

17.4.1.2 Iron Biofortification in Cereals

There are different strategies involved in the uptake of Fe by plants, as direct absorption and synthesis of mugineic acid (MA) or other secretions to chelate Fe (Connorton et al. 2017). There are many approaches in biofortification that improve Fe level in the edible plant part, i.e. seeds. The micronutrient content of cereals can be increased using the agronomic biofortification approach in which fertilizers are applied on the plant foliage or in the soil (Cakmak and Kutman 2017). It is considered a sustainable and cost-effective method (Garg et al. 2018). It takes a very short time to enrich edible seed with essential micronutrients such as Fe. Conventional breeding techniques and genetic engineering techniques are also used for the effective enrichment of Fe in food. The trait of interest must be available in the germplasm to produce the crop varieties rich in micronutrients such as Fe. Another focus is to increase the Fe content in seed coat and cotyledon to check

Table 17.1 Application of Zn in biofortification of cereals

Source of Zn	Application method	Fortified crop	Reference
Zn-coated urea (2.83 kg Zn ha^{-1})	Fertilization	Rice	Shivay et al. (2015)
PGPR (Zn solubilization) inoculation	Genetic biofortification	Soybean	Ramesh et al. (2014)
Soil applied $ZnSO_4$	Fertilizer application to soil	Iranian rice	Yadi et al. (2012)
$ZnSO_4$	Soil + foliar application	Wheat	Chattha et al. (2017)
ZnO (1% Zn)	Fertilization	Wheat	Shivay et al. (2008a, b)
$ZnSO_4$	Foliar application	Chickpea	Pathak et al. (2012)
Zn-EDTA	Fertilization	Rice	Naiq and Das (2008)
Zn + MN12 (endophytic bacterial strain *Pseudomonas* sp.)	Seed priming	Bread wheat	Rehman et al. (2018)
$ZnSO_4.7H_2O$	Foliar application	Wheat	Zhang et al. (2012)
Zn	Foliar application	Wheat	Zou et al. (2012)
$ZnSO_4.7H_2O$	Foliar application	Un-husked rice (whole grain with husk)	Phattarakul et al. (2012)
$ZnSO_4.7H_2O$	Soil application	Durum wheat (*Triticum durum*)	Hussain et al. (2012)
$ZnSO_4.7H_2O$	Fertilization	Rice	Saha et al. (2017)
Zn-EDTA	Fertilization	Lowland rice	Naiq and Das (2008)
$ZnSO_4$	Fertilization	Lowland rice	Naiq and Das (2008)

the role of polyphenols and phytate and their effect on the viability and establishment of seed. Mostly the Fe is accumulated in the vascular bundles (Cvitanich et al. 2010), whereas phytate accumulates in the vacuole of the plant cell (Panzeri et al. 2011). It is still under the determination that if Fe and phytate accumulate in the same cells. Therefore, the distribution of Fe and phytate at cellular and subcellular levels is an important key for the advancement of cotyledon biofortification (Punshon et al. 2013).

When Fe fertilizer application is done on plant foliage, almost 10 to 20 days are required for 50% absorption of Fe by the plant (Alshall and El-Ramady 2017). In this regard, soil application of Fe-EDTA (Ethylene Diamine Tetra Acetic acid) and nitrogen are more significant in terms of Fe absorption (Cakmak and Kutman 2017).

Table 17.2 Application of Fe in biofortification of cereals

Source of Fe	Crop	Application method	Reference
$FeSO_4$	Cowpea bean	Fertilization	Márquez-Quiroz et al. (2015)
Fe-EDTA	Cowpea bean	Fertilization	Márquez-Quiroz et al. (2015)
$FeSO_4$	Pea	Foliar spray	Kabir et al. (2016)
Overexpression of soybean ferritin gene	Maize	Genetic engineering	Aluru et al. (2011)
Ferritin gene	Rice	Transgenics	Masuda et al. (2012), Paul et al. (2014)
GmFERRITIN	Rice/Japonica cv. Kitaake	Genetic breeding technique	Goto et al. (1999)
GmFERRITIN	Maize/HiII (A188 _ B73) and Jubilee	Genetic breeding technique	Drakakaki et al. (2005)
$FeSO_4$	Foliar application	Wheat	Zhang et al. (2010)
Fe-EDTA	Soil application	Wheat	Aciksoz et al. 2011
Fe	wild emmer wheat, Triticum turgidum ssp. dicoccoides	Genetic biofortification	Peleg et al. (2008)
Fe amino acid (Fe-AA)	Brown rice	Foliar application	Yuan et al. (2013)

A study conducted by Yuan and coworkers showed that 14.5% increase in the concentration of Fe in plants was reported as a result of the application of Fe-AA (iron-amino acid) on foliage (Yuan et al. 2012). Exogenous application of Fe assists the crop in several ways that help the plant to achieve the maximum possible Fe level in seeds. Iron biofortified beans and pearl millet have improved the nutritional status of malnourished populations (Finkelstein et al. 2017). Various sources of Fe fertilizer have been used for fortification of different crops presented in Table 17.2.

A test was conducted at the University in Rwanda in which women having Fe-deficiency were given Fe biofortified beans for 4.5 months. It has increased the hemoglobin and overall body Fe level to a significant level (Haas et al. 2016). Another test was conducted in the Maharashtra region of India where secondary school-going children were facing Fe deficiency. They were given Fe biofortified pearl millet bread two times a day for 4 months. It has significantly reduced Fe-deficiency in children and is supposed to reduce Fe deficiency up to 64% by 6 months (Finkelstein et al. 2015).

17.4.1.3 Zinc and Iron Bioavailability and Bioaccumulation Aspects

Plants obtain Zn and Fe from the rhizosphere as these nutrients are not synthesized inside the plant (Morrissey and Guerinot 2009). Genetic engineering is widely used in many crops to enhance the micronutrient content in plants especially Fe and Zn. These transgenic strategies are aimed to increase the Fe and Zn content and their utilization by plants by the process of nodulation of transporters expression and reduction of anti-nutritional factors, i.e. phytic acid (Kerkeb et al. 2008). Several methods have been reported to produce genetically modified crops for better growth and fortification (Bashir et al. 2013). These approaches include reduction of anti-nutrient factors such as phytate, increasing the mobility of nutrients, i.e. Zn and Fe inside the plant and its binding capacity, increasing the number of metabolites to enhance nutrient absorption either directly or indirectly.

The use of nicotinamides is a biotechnological approach toward the enhancement of Fe and Zn concentration in crop plants (Grillet et al. 2014) as it acts as a metal chelator in both the monocots and dicots. Iron content can also be enhanced by the expression of ferritin and lacto ferritin (Rosa et al. 2017). Ferritin is a protein confined in plant plastid and acts as a nontoxic storage cell for Fe which can be released whenever needed by the plant. Ferritin can store almost 4500 atoms of Fe in the bioavailable form at one time (Darbani et al. 2013). Zinc is a crucial element in plant growth as it is a cofactor of almost 300 enzymes and more than 1000 transcription factors (Palmgren et al. 2008; Yadav et al. 2020). An increase in Zn bioavailability accompanied by Zn mobility and its translocation by the overexpression of genes is an important way to enhance the grain Zn content. For example, there are many cation specific transporters in rice, few of them are substrate-specific and few characterize cellular localization and expression patterns. Among these, CDF (cation diffusive facilitators) play a dominant role in translocation and uptake of Zn. The expression of nicotianamine synthetase (NA synthetase) can increase Zn levels by 2–3 folds in paddy (Lee et al. 2009).

17.4.1.4 Factors Affecting Availability of Zinc and Iron in Plants

Factors influencing the availability of Fe and Zn in plants are interrelated. These factors include parent material, the particle size distribution of soil, humus content, aeration, temperature, water content, and surface area of the root, mineral content, and development of mycorrhizae. Soil pH is a very important factor affecting the availability of nutrients in the soil. Some other factors are physiological factors, topographic factors, wind, atmosphere, frost damage, drainage, solar exposure, soil depth and organic content, etc. (Jackson 2008).

Soil Factors

Soil provides basic media of plant growth via the provision of anchoring space, water, and essential minerals. With diverse physico-chemical properties, soil also controls the availability of various nutrients to crop plants (Comerford 2005).

Nutrient chemistry in the soil is controlled by soil, environment, and agronomical practices prevailing there (Alloway 2009; Meena et al. 2020a). Among soil factors affecting nutrient dynamics, pH, total soil nutrients, organic matter contents, soil solution, pool chemistry, and plant-mediated influence on soil are important (Hacisalihoglu and Kochian 2003; Alloway 2009; White and Broadley 2011; Rehman et al. 2018).

Soil physico-chemical properties play an important role in nutrient availability and various nutrients (under the influence of soil properties) interact with each other and influence the solubility of counterparts. For example, Zn becomes available to plant in alkaline calcareous soils by making complexes with calcite. However, the increased availability of phosphorus can lower the availability of Zn in plants in arid and semi-arid soils (Alloway 2009; Noulas et al. 2018). Unavailable form of Zn exists in the form of oxides, silicates, and sulfides in the soil. Silicates exist as the most abundant unavailable Zn forms. There are some additional factors like redox potential, total sulfur in the soil, quantity of soluble bicarbonates present in soil which affect net availability of Zn (Impa and Johnson-Beebout 2012; Kumar et al. 2017b; Meena et al. 2019).

Maintenance of soil solution chemistry is a crucial concept of soil for proper nutrient supply. The solid phase is responsible for the maintenance of nutrient concentration in the solution phase. The transfer of nutrients from the solid phase to the solution phase involves biochemical processes (immobilization and mineralization) as well as physico-chemical processes (adsorption and desorption). In exhausted soils, the availability of nutrients in the soil solution is lower as compared to the plant's requirement which needs to be fulfilled. Moreover, the plants take up most nutrients from the soil solution which results in the deficiency of nutrients in the affected plant crops (Comerford 2005). Soil pH as affected by inter-conversion of carbonates and bicarbonates, soil calcareousness, root respiration, and homeostasis of acidic and basic ions in the soil–plant system affect nutrient dynamics (Hinsinger et al. 2003; Shen et al. 2004; Rehman et al. 2018). Altering rhizosphere pH has a great influence on the bioavailability of several nutrients like Fe, Zn, and P (Hinsinger et al. 2003; Loosemore et al. 2004). A minor increase in soil pH greatly influences the availability of these nutrients (Fageria et al. 2002) and high soil pH when coupled with high clay contents triggers net immobilization of Fe and Zn decreasing their availability to plants (Qadar 2002).

Among other constituents, organic matter is the one with enough capacity to provide a significant amount of various nutrients upon decomposition and its amount controls the release of nutrients. Soil poor in organic matter contents, when applied with a significant amount, can retain and provide much more nutrients to crop plants (Ozkutlu et al. 2006; Abat et al. 2012; Gurpreet-Kaur and Sharma 2013).

Plant Factors

The availability of Fe and Zn in plants also depends on several plant factors. The first factor is the contact of plant roots with nutrients in the soil as the availability and efficiency of nutrients depend largely on the contact between nutrients and the roots of the plant (Jungk 1984). The important plant factors that affect the availability of nutrient in plant system include root hairs, root surface area, the architecture of root, root crown development, anatomy of root structure, modification of rhizosphere structure and chemistry that can change pH of soil through proton exudation thereby increasing the nutrient availability and its diffusion through the root surface (Rose et al. 2013).

Environmental Factors

There are several biotic and abiotic environmental factors affecting the Fe and Zn availability to the plants. Biotic factors include weeds and parasitic plants, insects, pests, and fungi. Abiotic factors include climate (temperature, wind, and moisture), topography, and soil (Juneja et al. 2013). Deficiency of Zn is more prevalent among arid and semi-arid areas due to low top-soil water in rain-fed conditions (Cakmak et al. 1996).

Under limited moisture and water conditions, plants face an increased deficiency of essential nutrients such as Zn and Fe (Bagci et al. 2007). When moisture is low, the movement of Zn in the soil reduces which causes less availability of Zn to the plants (Marschner 2012). In water-limited conditions, plants deficient in Zn experience poor growth and are more susceptible to drought stress conditions (Bagci et al. 2007; Hajiboland and Amirazad 2010). Irrigation of drought-stressed plants along with Zn fertilizers can increase the grain yield in cereals.

Temperature is another environmental factor controlling soil nutrient pool chemistry and net availability to the plants. In cool and wet seasons, there is less availability of Zn and Fe to the plants (Moraghan and Mascagni 1991) because of less soil mineralization (i.e., the liberation of Zn or Fe from organic matter by decomposition) (Takkar and Walker 1993). Root growth, decomposition of organic matter, and mycorrhizal colonization are restricted in low temperature which limits the uptake of nutrients by plants (Moraghan and Mascagni 1991). Besides temperature, exposure to sunlight is also involved in nutrient homeostasis via modulating plant physiology and detoxification responses (Marschner and Cakmak 1989).

17.4.2 Conventional Breeding

Conventional breeding is the technique of biofortification in which plants are crossed in the research field to make a progeny that contains the characteristics of both parents. Conventional breeding done to obtain efficient nutrient acquiring (and accumulating) progeny can result in the production of lines with efficient nutrient use efficiency or fortified with required nutrients (Nestel et al. 2006). Many techniques are used for breeding that includes the scrutinization of germplasm variation to make genes more useful and tracking of target genes by using genetic markers. There are also various new techniques like tilling and mutations for saturation of metabolic pathways to produce high yielding and nutrient-rich varieties. Rice is the best example of conventionally bred crops. A rice variety containing high amounts of Fe and Zn bred with the high yielding variety of rice results in a progeny having high yield as well as increased concentration of micronutrients (Khush et al. 2012). Wheat is also considered for genetic variation (White and Broadley 2009) as there are two varieties of wheat, i.e. wild-type species and modern variety. After breeding of wheat, the enhanced concentration of Fe and Zn has been seen in modern varieties (Xu et al. 2011).

17.4.3 Genetic Modification Technique

In the genetic modification technique, a specific genetic trait is taken from the donor organism and transferred to the recipient organism that shows this trait afterwards. This technique is considered beneficial compared to the conventional breeding technique because it takes a very short time to produce a crop having traits of our interest and can transfer specific genes. Golden rice is one of the best examples of genetically modified crops (Potrykus 2001). In golden rice, beta-carotene was inserted as a trait of interest as rice does not produce beta-carotene. The genetically modified technique can also modify plants for the effective absorption of minerals from roots directly. It also can decrease anti-nutrients and increase the number of promoters in plants (White and Broadley 2009). An increase in the number of promoter compounds helps in the translocation of minerals in fruits and seeds.

17.4.4 Successful Biofortified Cereal Crops

With the availability of various biofortifying methods, cereals are mostly biofortified with micronutrients as their grains are highly consumed as a staple food (Rawat et al. 2013). For example, barley is fortified with Se to produce beer and as a result, it contained six times more Se compared to mother plant barley (Rodrigo et al. 2014). Oat fortified with Zn has also proved to be a very beneficial staple food in alleviating the deficiency of Zn. Biofortification of oats is mostly done by fertilization method or the seed coating with Zn-sulfate (Shivay et al. 2013). Wheat (*Triticum aestivum* L.) was biofortified with Zn in germplasm using genetic variability technique. It is possible in the condition when the soil contains an adequate Zn pool. Some varieties from India including BHU 1, 17, 19, and a few varieties from Pakistan including NR 420, 421, and 419 have shown an increase in the Zn content ranging between 4 and 10 ppm (Singla and Grover 2017). Moreover, an increase in Zn concentration in wheat grains and yield has been noticed by the use of agronomic biofortification techniques in areas having a severe lack of Zn. Yellow rust in wheat can be controlled by the use of Zn containing fertilizer along with pesticides (Ram et al. 2016).

Beans and pearl millet are biofortified with Fe to reduce Fe deficiency in malnourished populations (Sperotto et al. 2012). Almost 50 million of Indian rural population relies on pearl millet as their staple cereal food product. Iron-biofortified pearl millet flour contains more energy compared to the simple pearl millet flour that is not biofortified (Hama et al. 2012). Beans (*Phaseolus vulgaris* L.) were biofortified with Fe and Zn by CIAT (International Center for Tropical Agriculture) and two varieties NUA35 and NUA56 were developed. Both NUA35 and NUA56 bean grains showed an increase in Fe content of 18 and 23 mg kg^{-1} and Zn concentration of 8 and 7 mg kg^{-1}, respectively. Biofortified beans can be very helpful to tackle Fe and Zn deficiency as beans are used as a staple food product in America and Caribbean countries (Sharma et al. 2017) and are cultivated as a commercial product in Columbia and Uganda (Blair et al. 2010).

Rice is largely used as a staple food in the developing world. It is deficient in essential micronutrients like Fe and Zn, so the consuming population is suffering from Fe and Zn deficiency (Sperotto et al. 2012). Among women facing low Fe levels, consumption of biofortified rice can improve their total iron intake. A study was conducted in the Philippines in which 192 females were selected from 10 schools. High Fe rice and local rice variety were fed to the experimental groups and control subjects, respectively, for 9 months. High Fe rice contained 3.21 mg kg^{-1} of Fe, whereas local rice variety contained 0.57 mg kg^{-1} of Fe. Results have shown that biofortified rice added 1.79 mg of Fe to the daily dietary intake and local rice variety added 0.37 mg of Fe to the daily diet. There was a difference of 17% in the consumption of dietary Fe as compared to the control which increased body Fe level ($P = 0.6$) and ferritin level ($P = 0.10$), whereas no increase was noticed in hemoglobin level. Non-anemic women had shown a good response towards ferritin and total body Fe (Haas et al. 2005). In the nutrient-deficient soil, an increase in the yield of rice up to 7.2–14.8% has been observed by the application of Zn fertilizer using agronomic biofortification techniques (Ram et al. 2015).

The use of biomarkers to measure the Zn status is a new advancement in this field. Recent studies have shown that breaking of DNA strand indicates an increase in Zn, i.e. increased Zn concentration in biofortified crops (King et al. 2016). For the success of biofortified crops, some considerations must be kept in mind. The biofortified crop should be of high yield so that it provides the farmer with more profit (Sharma et al. 2017).

17.5 Recent Advances in Zinc and Iron Biofortification

Due to the immense population increase, the cultivation of high yielding cultivars has become a necessity for which somehow quality has got compromised. Different approaches have been applied to facilitate the dietary supplementation of Fe and Zn. These approaches comprise food fortification, supplementation, crop biofortification, and dietary diversification (Gregory et al. 2017). Biofortification is a sustainable, cost-effective, and long-term approach for the provision of micronutrients to poor communities of developing countries. For biofortification of cereal crops, the application of nanotechnology has opened some promising dimensions like Fe and Zn enrichment in cereal grains (Nazir et al. 2016). Besides these, the use of biofertilizers/microbial consortia and the use of various amendments are important aspects.

17.5.1 Use of Biofertilizers

The substance that contains living organisms or derived products that helps in plant growth is called biofertilizer. It is mostly applied in the rhizosphere portion of plant roots where it increases the availability of micronutrients, hence increasing the growth of the plant (Jangir et al. 2016). Plant Growth Promoting Rhizobacteria

(PGPR) is best-known biofertilizers as they help plant growth via various mutualistic phenomena: N_2 fixation, phosphorus, Zn, and Fe solubilization, and plant growth stimulation via plant growth stimulating substances. Application of these biofertilizers can increase soil nutrient bioavailability and thus help in biofortification (Billard et al. 2014; Seyed Sharifi 2016; Shukla and Mishra 2018). The application of PGPR has proven beneficial in increasing tomato biomass and the uptake of nitrate (Olivares et al. 2015). In a study, four efficient bacterial strains were selected to check their Zn solubilization abilities in wheat (*Triticum aestivum*) varieties, i.e. Gw-366 and LK-1. Treatment of Gw-366 variety with MS-ZT10 (*Exiguobacterium aurantiacum* strain) has increased the Zn and Fe content (18.2 and 24.67 ppm) by six-folds over the initial values. The levels of N, P, and K are also enhanced to a greater extent (Shaikh and Saraf 2017).

17.5.2 Nano-fertilizer Application

Nanotechnology is an emerging discipline in the manufacturing of nano-size particles (size 1–100 nm), which can be beneficial for agroecosystems in many ways (Chinnamuthu and Boopathi 2009). Nanotechnology is serving as a potential strategy towards increasing the growth and production of crops and pest management. Nowadays, nanoparticles are being used for making advanced pesticides and fertilizers. Nanotechnology has improved the working efficiency of fertilizers (Khan and Rizvi 2017). Nano-fertilizers, being in nano size, can deliver nutrients to crops very efficiently (De Rosa et al. 2010). Nano fertilizers are playing a crucial role in the sustainability of agriculture and helping to ensure the provision of food to meet global food demand. They are the best alternatives in alleviating essential nutrient deficiencies and chronic effects of eutrophication (Shukla et al. 2019). They are synthesized keeping in view the demand for crops while minimizing the differential losses and increasing the potentiality of crops (Yang et al. 2015). For example, nano formulations of nitrogenous fertilizers can synchronize their release with the nitrogen demand of crops. Nano fertilizers can reduce the nutrient losses as they are directly internalized in the crops thereby reducing their contact with soil or water (Panpatte et al. 2016). A wide range of nano-fertilizers like polymeric nanoparticles, Zn oxide nanoparticles, and Fe oxide nanoparticles can be used in agriculture (Khan and Rizvi 2017).

Nano-fertilizers are slow-release fertilizers that improve the growth as well as the health of plants (Naderi and Danesh-Shahraki 2013). These nano-fertilizers can also work in a combination of nano-devices that detect the release of nutrients from the soil and synchronize its uptake by the plant. In this way, the loss of nutrients can be minimized by decreasing the contact of nutrients with microbes and soil; therefore, nutrients become more available to the plant (De Rosa et al. 2010). Encapsulation of micronutrients within the nanoparticle is very effective in enhancing the fertilizer use efficiency. It can be done in three ways, viz. (1) Coating with a thin polymer film, (2) Coating with nano-emulsion, and (3) Encapsulation with nonporous dimensions (Rai et al. 2012).

Root exudates can be used to prepare nano-biosensors that are further incorporated as nano-fertilizers (Sultan et al. 2009; Al-Amin Sadek and Jayasuriya 2007). Nano-clay and zeolites can increase fertilizer use efficiency. They have a honeycomb-like structure that contains N, P, K, Ca, and trace elements. So, they act as a complete nutrient supply that is released on demand (Chinnamuthu and Boopathi 2009). Ammonia-charged zeolites can enhance the uptake of P by plants by increasing the solubilization of phosphate minerals and increase the yield of the crop as well. Zeolite chips fertilized with urea can be used as a slow-release N-fertilizer. Coating of nano and sub-nano composites is done to control the release of micronutrients from the fertilizer capsule (Liu et al. 2006). In a study, it has been proved that the incorporation of fertilizer in the cochleate nanotube can enhance the crop yield (De Rosa et al. 2010). Application of nanoparticles like ZnO has reportedly increased the germination and root elongation in maize and cabbage (Pokhrel and Dubey 2013).

17.5.3 Zinc and Iron Fortified Food

There are several biofortified crops having first-generation traits are now in use in both developing as well as developed countries (Qaim 2009; Raney 2006). The biofortified crops are an effective alternative to alleviate the burden of micronutrient malnourishment in developing regions where the daily calorie intake of people depends solely on staple cereal foods such as wheat and rice (Ye et al. 2000). The main focus is the enhancement of Fe and Zn in staple cereal crops over the past few decades. There are some examples of biofortified cereal foods including the best example of Golden rice. It was genetically engineered with the bacterium (Erwinia previously known as Pantoea) and transgenes from daffodil. In China, Philippines, and India, Golden rice reduced vitamin A deficiency within a range of 17–60, 6–32, and 9–59% respectively (De Steur et al. 2015). In mineral-enriched rice, the content of Fe, Zn, and Cu are enhanced as a result of overexpression of single rice gene (Lee et al. 2009). Another example is the white corn with enhanced levels of folate, beta-carotene, and ascorbate (Naqvi et al. 2009). In China, multi-biofortified rice (biofortified with Fe, Zn, folate, and pro-vitamin A) and folate-biofortified rice have successfully reduced micronutrient malnutrition by 11–46 and 20–82%, respectively. Golden rice has opened up ways to the production of more nutrient-rich biofortified staple crops such as bean, cassava, corn, wheat, and potato. Moreover, successful biofortification of yellow corn with pro-vitamin A has alleviated micronutrient deficiency to the desired levels (Azmach et al. 2013).

Plant-based products contain a wide range of those micronutrients that exhibit a vital role in the health and nutrition of humans. There are different strategies used to enhance the nutrient deficiency of our staple foods to serve this purpose. These strategies have a target to increase the nutrient content, increase the level of amino acid, antioxidants, and improve the composition of fatty acid in plants (Hirschi 2009). Conventional breeding approaches have great potential in increasing the micronutrient content of staple foods and there were also genetic breeding techniques in which nutritionally rich cultivars were selected for further cultivation. The cultivars having high micronutrient content and high yield are bred in genetic breeding. It is a very economic method of crop cultivation with high nutrient content.

The successful fortified crops using conventional breeding techniques till now include orange-flesh sweet potato with increased β-carotene levels over 200 $\mu g\ g^{-1}$ and beans with increased Fe levels in grains up to 50–70%. Similarly, β-carotene was inserted in the endosperm of rice varieties making an advanced breeding line named Golden rice which contains 37 $\mu g\ g^{-1}$of carotenoid in which 31 $\mu g\ g^{-1}$ β-carotene was in the available form (Paine et al. 2005).

17.5.4 Soil Zinc and Iron Solubilizing Consortia Application

The characterization and isolation of a group of bacteria having the capability of making soil nutrients bioavailable are termed as solubilizing consortia. Different experiments have been conducted to check the solubility potential of Zn for various bacterial consortia. Commonly used Zn-solubilizing bacteria are ZnSB and $ZnSB_2$, *B. megaterium*, and KY687496. Among these Zn-solubilizing bacteria, the most useful and potent one is KY687496. Some studies have proved that $ZnSB_2$ has increased the dissolution rate of Zn and decreased the application of inorganic Zn. Therefore, when Zn is applied along with consortium, it has more Zn solubilization ability and disease suppression ability (Dinesh et al. 2018). Inoculation of bacteria and fungi into the soil can also increase the solubilization of Zn (Tariq et al. 2007). Well-known Zn solubilizers are *Pencillium bilaji, Pseudomonas,* and *Bacillus* that have the ability to solubilize ZnO, $ZnCO_3$, and ZnS for the plants (Saravanan et al. 2007).

Iron is also an essential element for plant growth. According to a study, *Pantoea dispersa* MPJ9, *Pseudomonas putida* MPJ6 are Fe-chelating rhizobacteria which have the potential of siderophore production can improve Fe availability significantly. The naturally occurring micro-flora and fauna also act as the best solubilizers for many micronutrients such as Zn and Fe (Chen et al. 2003). These microorganisms increase the availability of Zn to the plants by increasing its solubility in the soil (Subramanian et al. 2009).

Inoculation of *Azotobacter* and *Azospirillum* has also reported to increase the bioavailability of Zn in the grains. An experiment has proved that there are two folds more concentration of Zn in the shoot of *Thlaspi caerulescens* receiving biofertilizer as compared to that of the control treatment (Whiting et al. 2001). The association of mycorrhizal fungi with plants also positively increase the nutrient uptake by plants (Tariq et al. 2007). Inoculation of bacteria relieves the nutrient deficiency symptoms in the plants (Hussain et al. 2015) and can also help to increase the biomass and grain yield of crops (Tariq et al. 2007). For maximum benefits, different in many cases, the multi-strain consortium is used instead of a single strain and it performs well in comparison to the single strain (Ramesh et al. 2014).

17.5.5 Organic and Inorganic Amendments Application

Modern crop varieties need an increased quantity of nutrients for their better growth and high yield (Khush 2001; Cakmak 2002; Sihag et al. 2015; Kumar et al. 2017). So, these varieties have depleted the soil with the essential nutrients like Fe and Zn, which have now become less available in the soil. A practical strategy to combat micronutrient deficiency is the use of different organic and inorganic amendments, i.e. the use of Fe and Zn fertilizers for biofortification of crops (Gogos et al. 2013). Mostly, the inorganic fertilizers are immobilized, mineralized, or adsorbed in the soil (Jangir et al. 2019; Kumar et al. 2020). Farmyard manure, poultry manure, and sewage sludge can be used as organic amendments (Meena et al. 2018). They provide micronutrients such as Zn and Fe to the soil in quite an effective way and resolve the problem of micronutrient deficiency in soils, especially alkaline calcareous soils. Moreover, organic amendments have the ability to improve the chemical, physical, and biological properties of soil in a very effective way (Tolay and Gulmezoglu 2004; Kumar et al. 2017a). Use of $ZnSO_4$ in combination with organic manure has improved the uptake of Zn by plants successfully (Akinrinde et al. 2006). Farmyard manure, olive husk, and compost have also improved the uptake of Zn by plants (Clemente et al. 2007). Organic amendments have also improved the soil fertility, enzyme activities, and the activities of microbes in the soil (Liang et al. 2003). In a study, the hydrolyzed wool was used as an amendment on wheat (*Triticuma estivum* var. *Greina*) to investigate the uptake of Fe and Zn in it. It successfully improved the grain Zn content by 54.1 mg kg^{-1}, while in control treatment, grain Zn was 37.7 and 45.5 mg kg^{-1} in mineral fertilization. It also improved grain yield by two-fold and grain protein content by 1.5-fold (Gogos et al. 2013). The use of EDTA also has the potential to improve the Zn uptake by plants in contaminated soils. It can transform the unavailable soil Zn fraction to the available Zn fraction in the calcareous soils (Wang et al. 2017).

17.6 Future Challenges in Zinc and Iron Biofortification

Biofortification of cereals has been proven to be a sustainable approach in combating malnutrition in poor countries where cereals are the main food component. In many countries, biofortification has been introduced as the best strategy to eradicate micronutrient malnutrition and improvement of human health. Agronomic biofortification (enhancement of micronutrients quantity in crops by fertilization), conventional breeding technique, and genetic breeding technique are used to produce biofortified crops. Maize, rice, wheat, millet, beans, cassava, and sweet potato have been successfully biofortified with essential nutrients such as Fe and Zn till now. In future, agronomic and genetic biofortification techniques need to be integrated for easy transportation of minerals to the phloem tissues of plants. There is also an urgent need for the identification of those mechanisms that affect the mineral-homeostasis in plant cells. Efficient use of a combination of biofortification techniques, i.e. conventional breeding and enhanced fertilization of essential nutrients is needed. Evaluation and monitoring programs are needed for keeping the record of available biofortification technologies and stakeholders funding for those biofortification technologies. Harvest Plus consortium is a program that is successfully doing its job in the evaluation of biofortification techniques (Andersson 2017). Moreover, communication and marketing strategies are also needed in this regard, for further production and sale of biofortified crops. The same marketing strategies are not acceptable in all countries (Wakeel et al. 2018).

Further research areas in biofortification include testing the efficiency of biofortified crops for each age group. According to nutritionists, biofortified food crops can improve the health and cure the micronutrient malnutrition but still more research is needed in knowing the nutritional status of biofortified food crops considering the biochemical and functional indicators.

Advanced technologies including the biotechnological approaches, i.e. DNA markers and gene transfer that are competing with the conventional breeding and genetic breeding techniques as it reduces the time taken to produce cultivars with improved Zn and Fe. In molecular marker techniques, markers can facilitate the crossing of genes for improving desirable micronutrients into new breeding lines. At present, it is challenging to improve the concentrations of Fe and Zn because of the lower fertilizer use efficiency (Cakmak et al. 2010). Authors encourage readers to consume biofortified cereal crops to cope with Fe and Zn deficiency, especially for growing children. Moreover, a comprehensive database of fortified cereal crops is also a requirement for today which can be helpful in the selection of food.

17.7 Conclusions

The most serious health issue faced by billions of people worldwide is the deficiency of essential nutrients. People living in developing countries like Asia, Africa, and Latin America consume cereals as a staple food. These cereals are greatly deficient in Fe and Zn that perform various important physiological functions in the human body. As a result of Fe and Zn deficiency, people are suffering from hidden hunger at a global scale. Alleviation of Fe and Zn deficiency in the diet is a huge challenge for which different strategies have been used till now. Among all the strategies, biofortification is considered the most efficient one because of its cost-effectiveness and high sustainability. Biofortification of staple cereal crops ensures the access of nutritious food to people. It is equally beneficial for all age groups including infants, adolescents, pregnant women, and aged people as well. Different techniques have been used for biofortifying food crops such as agronomic biofortification, conventional breeding technique, and genetic modification technique. Apart from this, there are various advancements in this field like the use of nano-fertilizers and biofertilizers. All these strategies are adaptable, varying according to the regions and countries in the world. Biofortification is considered as the most feasible means of providing the rural and poor population with nutritious staple food.

References

Abat M, McLaughlin MJ, Kirby JK, Stacey SP (2012) Adsorption and desorption of copper and zinc in tropical peat soils of Sarawak, Malaysia. Geoderma 175–176:58–63

Aciksoz SB, Yazici A, Ozturk L, Cakmak I (2011) Biofortification of wheat with iron through soil and foliar application of nitrogen and iron fertilizers. Plant and Soil 349:215–225. https://doi.org/10.1007/s11104-011-0863-2

Akinrinde EA, Bello OS, Olubkin OA, Ahmed AA (2006) Changes in soil pH and maize contents of zinc and phosphorous under zinc sulphate and organic waste application. Glob J Agric Sci 5:49–56. https://doi.org/10.4314/gjass.v5i1.2282

Al-Amin Sadek MD, Jayasuriya HP (2007) Nanotechnology prospects in agricultural context: an overview. In: Proceedings of the international agricultural engineering conference, 3–-6 December 2007, Bangkok, p 548

Alloway BJ (2009) Soil factors associated with zinc deficiency in crops and humans. Environ Geochem Health 31:537–548. https://doi.org/10.1007/s10653-009-9255-4

Alshall T, El-Ramady H (2017) Foliar application: from plant nutrition to biofortification. Environ Biodiver Soil Secur 1:71–83

Aluru MR, Rodermel SR, Reddy MB (2011) Genetic modification of low phytic acid 1-1maize to enhance iron content and bioavailability. J Agric Food Chem 59:12954–12962. https://doi.org/10.1021/jf203485a

Andersson M (2017) Progress update: crop development of biofortified staple food crops under harvest plus. African J Food Agric Nutr Dev 17:11905–11935. https://doi.org/10.18697/ajfand.78.harvestplus05

Azmach G, Gedil M, Menkir A, Spillane C (2013) Marker-trait association analysis of functional gene markers for provitamin A levels across diverse tropical yellow maize inbred lines. BMC Plant Biol 13(1):227

Bagci SA, Ekiz H, Yilmaz A, Cakmak I (2007) Effects of zinc deficiency and drought on grain yield of field-grown wheat cultivars in Central Anatolia. J Agron Crop Sci 193:198–206

Bashir K, Takahashi R, Nakanishi H, Nishizawa NK (2013) The road to micronutrient biofortification of rice: progress and prospects. Front Plant Sci 4:15. https://doi.org/10.3389/fpls.2013.00015

de Benoist B, McLean E, Egli I, Cogswell M (2008) Worldwide prevalence of anaemia 1993–2005: WHO global database on anaemia. World Health Organization, Geneva. http://www.who.int/vmnis/anaemia/prevalence/

Bhullar NK, Gruissem W (2013) Nutritional enhancement of rice for human health: the contribution of biotechnology. Biotechnol Adv 31(1):50–57

Billard V, Etienne P, Jannin L, Garnica M, Cruz F, Garcia-Mina JM, Yvin JC, Ourry A (2014) Two biostimulants derived from algae or humic acid induce similar responses in the mineral content and gene expression of winter oilseed rape (*Brassica napus* L.). J Plant Growth Regul 33:305–316. https://doi.org/10.1007/s00344-013-9372-2

Black R (2003a) Micronutrient deficiency—an underlying cause of morbidity and mortality. Bull World Health Organ 81(03808):79

Black RE (2003b) Zinc deficiency, infectious disease and mortality in the developing world. J Nutr 133:1485S–1489S

Black RE, Allen LH, Bhutta ZA, Caulfield LE, De Onis M, Ezzati M, Mathers C, Rivera J, Maternal, Child Undernutrition Study Group (2008) Maternal and child undernutrition: global and regional exposures and health consequences. Lancet 371:243–260. https://doi.org/10.1016/s0140-6736(07)61690-0

Blair MW, Monserrate F, Beebe SE, Restrepo J, Flores JO (2010) Registration of high mineral common bean germplasm lines NUA35 and NUA56 from the Red-Mottled Seed Class. J Plant Regist 4:55–59. https://doi.org/10.3198/jpr2008.09.0562crg

Bothwell, MacPhail (2004) The potential role of NaFeEDTA as an iron fortificant. Int J Vitam Nutr Res 74:421–434. https://doi.org/10.1024/0300-9831.74.6.421

Bouis HE (2003) Micronutrient fortification of plants through plant breeding: can it improve nutrition in man at low cost? Proc Nutr Soc 62:403–411

Bouis HE, Hotz C, McClafferty B, Meenakshi JV, Pfeiffer WH (2011) Biofortification: a new tool to reduce micronutrient malnutrition. Food Nutr Bull 32:S31–S40. https://doi.org/10.1177/15648265110321s105

Brown PH, Cakmak I, Zhang Q (1993) Form and function of zinc plants. In: Zinc in soils and plants. Springer, Dordrecht, pp 93–106

Cakmak I (2002) Plant nutrition research: priorities to meet human needs for food in sustainable ways. Plant and Soil 247:3–24

Cakmak I (2008) Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? Plant and Soil 302:1–17. https://doi.org/10.1007/s11104-007-9466-3

Cakmak I (2012) Harvest plus zinc fertilizer project: harvest zinc. Better Crops 96:17–19

Cakmak I, Kutman UB (2017) Agronomic biofortification of cereals with zinc: a review. Eur J Soil Sci 69:172–180. https://doi.org/10.1111/ejss.12437

Cakmak I, Yilmaz A, Kalayci M, Ekiz H, Torun B, Erenoglu B, Braun HJ (1996) Zn deficiency as a critical problem in wheat production in central Anatolia. Plant and Soil 180:165–172

Cakmak I, Pfeiffer WH, McClafferty B (2010) Review: biofortification of durum wheat with zinc and iron. Cereal Chem J 87:10–20. https://doi.org/10.1094/cchem-87-1-0010

Carvalho SMP, Vasconcelos MW (2013) Producing more with less: strategies and novel technologies for plant-based food biofortification. Food Res Int 54:961–971. https://doi.org/10.1016/j.foodres.2012.12.021

Caulfield LE (2004) Maternal zinc deficiency and maternal and child health in Peru. Nutr Today 39:78–87. https://doi.org/10.1097/00017285-200403000-00010

Chattha MU, Hassan MU, Khan I, Chattha MB, Mahmood A, Nawaz M, Khan S (2017) Biofortification of wheat cultivars to combat zinc deficiency. Front Plant Sci 8:281

Chen BD, Li XL, Tao HQ (2003) The role of arbuscular mycorrhiza in zinc uptake by red clover growing in a calcareous soil spiked with various quantities of zinc. Chemosphere 50:839–846

Chinnamuthu CR, Boopathi PM (2009) Nanotechnology and agroecosystem. Madras Agric J 96:17–31

Clemente R, Paredes C, Bernal MP (2007) A field experiment investigating the effects of olive husk and cow manure on heavy metal availability in a contaminated calcareous soil from Murcia (Spain). Agric Ecosyst Environ 118:319–326. https://doi.org/10.1016/j.agee.2006.06.002

Comerford NB (2005) Soil factors affecting nutrient bioavailability. In: Nutrient acquisition by plants. Springer, New York, pp 1–14

Connorton JM, Balk J, Rodríguez-Celma J (2017) Iron homeostasis in plants—a brief overview. Metallomics 9:813–823. https://doi.org/10.1039/c7mt00136c

Conrad ME, Umbreit JN, Moore EG (1999) Iron absorption and transport. Am J Med Sci 318:213–229. https://doi.org/10.1016/s0002-9629(15)40626-3

Cvitanich C, Przybyłowicz WJ, Urbanski DF (2010) Iron and ferritin accumulate in separate cellular locations in Phaseolus seeds. BMC Plant Biol 10:26. https://doi.org/10.1186/1471-2229-10-26

Darbani B, Briat JF, Holm PB, Husted S, Noeparvar S, Borg S (2013) Dissecting plant iron homeostasis under short and long-term iron fluctuations. Biotechnol Adv 31:1292–1307. https://doi.org/10.1016/j.biotechadv.2013.05.003

De Rosa MR, Monreal C, Schnitzer M, Walsh R, Sultan Y (2010) Nanotechnology in fertilizers. Nat Nanotechnol J 5:91

De Steur H, Blancquaert D, Strobb S, Lambert W, Gellynck X, Van Der Straeten D (2015) Status and market potential of transgenic biofortified crops. Nat Biotechnol 33(1):25–29. https://doi.org/10.1038/nbt.3110

Dinesh R, Srinivasan V, Hamza S, Sarathambal C, Gowda SA, Ganeshamurthy AN, Gupta SB, Nair VA, Subila KP, Lijina A, Divya VC (2018) Isolation and characterization of potential Zn solubilizing bacteria from soil and its effects on soil Zn release rates, soil available Zn and plant Zn content. Geoderma 321:173–186. https://doi.org/10.1016/j.geoderma.2018.02.013

Drakakaki G, Marcel S, Glahn RP, Lund EK, Pariagh S, Fischer R, Christou P, Stoger E (2005) Endosperm-specific co-expression of recombinant soybean ferritin and Aspergillus phytase in maize results in significant increases in the levels of bioavailable iron. Plant Mol Biol 59:869–880

Fageria NK, Stone LF (2008) Micronutrient deficiency problems in South America. In: Micronutrient deficiencies in global crop production. Springer, New York, pp 245–266

Fageria NK, Baligar VC, Clark RB (2002) Micronutrients in crop production. Adv Agron 77:189–272

Finkelstein JL, Mehta S, Udipi SA (2015) A randomized trial of iron-biofortified pearl millet in school children in India. J Nutr 145:1576–1581. https://doi.org/10.3945/jn.114.208009

Finkelstein JL, Haas JD, Mehta S (2017) Iron-biofortified staple food crops for improving iron status: a review of the current evidence. Curr Opin Biotechnol 44:138–145

Fukao Y, Ferjani A, Tomioka R, Nagasaki N, Kurata R, Nishimori Y, Fujiwara M, Maeshima M (2011) iTRAQ analysis reveals mechanisms of growth defects due to excess zinc in Arabidopsis. Plant Physiol 155:1893–1907. https://doi.org/10.1104/pp.110.169730

García-Bañuelos ML, Sida-Arreola JP, Sánchez E (2014) Biofortification—promising approach to increasing the content of iron and zinc in staple food crops. J Elem 19(3):865–888

Garg M, Sharma N, Sharma S, Kapoor P, Kumar A, Chunduri V, Arora P (2018) Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. Front Nutr 5:12. https://doi.org/10.3389/fnut.2018.00012

Gibson RS (2012) Zinc deficiency and human health: etiology, health consequences, and future solutions. Plant and Soil 361(1–2):291–299

Gogos A, Evangelou MWH, Schäffer A, Schulin R (2013) Hydrolysed wool: A novel soil amendment for zinc and iron biofortification of wheat. New Zeal J Agric Res 56:130–141. https://doi.org/10.1080/00288233.2013.775165

Gomez-Galera S, Rojas E, Sudhakar D, Zhu C, Pelacho AM, Capell T, Christou P (2010) Critical evaluation of strategies for mineral fortification of staple food crops. Trans Res 19(2):165–180

Goto F, Yoshihara T, Shigemoto N, Toki S, Takaiwa F (1999) Iron fortification of rice seed by the soybean ferritin gene. Nat Biotechnol 17:282–286

Gregory PJ, Wahbi A, Adu-Gyamfi J, Heiling M, Gruber R, Joy EJ, Broadley MR (2017) Approaches to reduce zinc and iron deficits in food systems. Glob Food Sec 15:1–10. https://doi.org/10.1016/j.gfs.2017.03.003

Grillet L, Mari S, Schmidt W (2014) Iron in seeds—loading pathways and subcellular localization. Front Plant Sci 4:535. https://doi.org/10.3389/fpls.2013.00535

Gurpreet-Kaur SBD, Sharma S (2013) Effects of organic matter and ionic strength of supporting electrolyte on zinc adsorption in benchmark soils of Punjab in Northwest India. Commun Soil Sci Plant Anal 44:922–938

Haas JD, Beard JL, Murray-Kolb LE, Mundo AM, Felix A, Gregorio GB (2005) Iron- biofortified rice improves the iron stores of nonanemic Filipino women. J Nutr 135(12):2823–2830

Haas JD, Luna SV, Lung'aho MG, Wenger MJ, Murray-Kolb LE, Beebe S, Gahutu JB, Egli IM (2016) Consuming iron biofortified beans increases iron status in Rwandan women after 128 days in a randomized controlled feeding trial. J Nutr 146:1586–1592. https://doi.org/10.3945/jn.115.224741

Hacisalihoglu G, Kochian LV (2003) How do some plants tolerate low levels of soil zinc? Mechanisms of zinc efficiency in crop plants. New Phytol 159:341–350. https://doi.org/10.1046/j.1469-8137.2003.00826.x

Hajiboland R, Amirazad F (2010) Growth, photosynthesis and antioxidant defense system in Zn–deficient red cabbage plants. Plant Soil Environ 56:209–217

Hama F, Icard-Vernière C, Guyot JP, Rochette I, Diawara B, Mouquet-Rivier C (2012) Potential of non-GMO biofortified pearl millet (*Pennisetum glaucum*) for increasing iron and zinc content and their estimated bioavailability during abrasive decortication. Int J Food Sci Technol 47:1660–1668. https://doi.org/10.1111/j.1365-2621.2012.03017.x

Henderson L, Gregory J, Swan G (2003) The national diet and nutrition survey: Adults aged 19 to 64 years. The Stationery Office, London

Hinsinger P, Plassard C, Tang CX, Jaillard B (2003) Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: a review. Plant and Soil 248:43–59

Hirschi KD (2009) Nutrient biofortification of food crops. Annu Rev Nutr 29:401–421

Hoekenga OA (2014) Genomics of mineral nutrient biofortification: calcium, iron and zinc. In: Genomics of plant genetic resources. Springer, Dordrecht, pp 431–454

Hussain A, Arshad M, Zahir ZA, Asghar M (2015) Prospectus of zinc solubilizing bacteria for improving growth and physiology of maize. Pak J Agri Sci 52:915–922

Hussain S, Maqsood MA, Rengel Z, Aziz T (2012). Biofortification and estimated human bioavailability of zinc in wheat grains as influenced by methods of zinc application. Plant and Soil 361 (1-2):279–290

Impa SM, Johnson-Beebout SE (2012) Mitigating zinc deficiency and achieving high grain Zn in rice through integration of soil chemistry and plant physiology research. Plant and Soil 361:3–41. https://doi.org/10.1007/s11104-012-1315-3

Iyengar GV, Nair PP (2000) Global outlook on nutrition and the environment: meeting the challenges of the next millennium. Sci Total Environ 249:331–346. https://doi.org/10.1016/s0048-9697(99)00529-x

Jackson RS (2008) Site selection and climate. In: Wine science. Elsevier, Amsterdam, pp 239–269

Jangir CK, Singh D, Kumar S (2016) Yield and economic response of biofertilizer and fertility levels on black gram (*Vigna mungo* L.). Prog Res–An Int J 11:5252–5254

Jangir CK, Kumar S, Lakhran H, Meena RS (2017) Towards mitigating malnutrition in pulses through biofortification. Trends Biosc 10(17):2999–3002

Jangir CK, Kumar S, Meena RS (2019) Significance of soil organic matter to soil quality and evaluation of sustainability. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 357–381

Juneja A, Ceballos R, Murthy G (2013) Effects of environmental factors and nutrient availability on the biochemical composition of algae for biofuels production: A review. Energies 6:4607–4638. https://doi.org/10.3390/en6094607

Jungk A (1984) Soil and plant factors affecting availability of mineral nutrients. Acta Hortic 145:165–172. https://doi.org/10.17660/actahortic.1984.145.17

Jyung WH, Ehmann A, Schlender KK, Scala J (1975) Zinc nutrition and starch metabolism in *Phaseolus vulgaris* L. Plant Physiol 55:414–420

Kabir AH, Paltridge N, Stangoulis J (2016) Chlorosis correction and agronomic biofortification in field peas through foliar application of iron fertilizers under Fe deficiency. J Plant Interact 11 (1):1–4

Katyal JC, Rattan RK (2003) Secondary and micronutrients research gaps and future needs. Fertiliser News 48:9–20

Kerkeb L, Mukherjee I, Chatterjee I, Lahner B, Salt DE, Connolly EL (2008) Iron-induced turnover of the Arabidopsis iron-regulated transporter1 metal transporter requires lysine residues. Plant Physiol 146:1964–1973. https://doi.org/10.1104/pp.107.113282

Khan MR, Rizvi TF (2017) Application of nanofertilizer and nanopesticides for improvements in crop production and protection. Nanosci Plant–Soil Syst 48:405–427

Khush GS (2001) Challenges for meeting the global food and nutrient needs in the new millennium. Proc Nutr Soc 60:15–26. https://doi.org/10.1079/pns200075

Khush GS, Lee S, Cho J-I, Jeon J-S (2012) Biofortification of crops for reducing malnutrition. Plant Biotechnol Rep 6:195–202. https://doi.org/10.1007/s11816-012-0216-5

King J, Brown K, Gibson R, Krebs N, Lowe N, Siekmann J, Raiten D (2016) Biomarkers of nutrition for development—zinc review. J Nutr 146(4):858S–885S. https://doi.org/10.3945/jn.115.220079

Kumar S, Singh MK, Meena RS, Hingonia K (2017) Influence of crop geometry and cultivars on growth, yield and production efficiency of dry direct-seeded rice (*Oryza sativa* L.). J Appl Nat Sci 9(4):2469–2476

Kumar S, Jakhar SR, Dahiya S, Jangir CK, Meena RS (2017a) Soil sickness and productivity from ecological aspects. J Pharm Phytochem 6:827–831

Kumar S, Meena RS, Pandey A, Seema (2017b) Soil acidity management and an economics response of lime and sulfur on sesame in an alley cropping system. Int Curr Microb Appl Sci 6(3):2566–2573

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, Singapore, pp 337–375. https://doi.org/10.1007/978-981-13-7264-3_10

Lee S, Jeon US, Lee SJ, Kim YK, Persson DP, Husted S, Schjørring JK, Kakei Y, Masuda H, Nishizawa NK, An G (2009) Iron fortification of rice seeds through activation of the nicotianamine synthase gene. Proc Natl Acad Sci U S A 106:22014–22019. https://doi.org/10.1073/pnas.0910950106

Liang Y, Yang Y, Yang C, Shen Q, Zhou J, Yang L (2003) Soil enzymatic activity and growth of rice and barley as influenced by organic manure in an anthropogenic soil. Geoderma 115:149–160. https://doi.org/10.1016/s0016-7061(03)00084-3

Liu X, Feng Z, Zhang S, Zhang J, Xiao Q, Wang Y (2006) Preparation and testing of cementing nano-sub nano composites of slow or controlled release of fertilizers. Sci Agric Sin 39:1598–1604

Liu H, Gan W, Rengel Z, Zhao P (2016) Effects of zinc fertilizer rate and application method on photosynthetic characteristics and grain yield of summer maize. J Soil Sci Plant Nutr 16 (2):550–562. https://doi.org/10.4067/s0718-95162016005000045

Loosemore N, Straczek A, Hinsinger P, Jaillard B (2004) Zinc mobilization from a contaminated soil by three genotypes of tobacco as affected by soil and rhizosphere pH. Plant and Soil 260:19–32

Lowe NM, Fekete K, Decsi T (2009) Methods of assessment of zinc status in humans: a systematic review. Am J Clin Nutr 89:2040S–2051S. https://doi.org/10.3945/ajcn.2009.27230g

Márquez-Quiroz C, De-la-Cruz-Lázaro E, Osorio-Osorio R, Sánchez-Chávez E (2015) Biofortification of cowpea beans with iron: iron's influence on mineral content and yield. J Soil Sci Plant Nutr 15(4):839–847

Marschner H (1995) Beneficial mineral elements. In: Mineral nutrition of higher plants. Academic Press, London, pp 405–435

Marschner P (2012) Marschner's mineral nutrition of higher plants, 3rd edn. Academic Press, London

Marschner H, Cakmak I (1989) High light intensity enhances chlorosis and necrosis in the leaves of zinc, potassium and manganese deficient bean (*Phaseolus vulgaris* L.) plants. Plant Physiol 134:308–315

Masuda H, Ishimaru Y, Aung MS, Kobayashi T, Kakei Y, Takahashi M, Nishizawa NK (2012) Iron biofortification in rice by the introduction of multiple genes involved in iron nutrition. Sci Rep 2:543

Mayer JE, Pfeiffer WH, Beyer P (2008) Biofortified crops to alleviate micronutrient malnutrition. Curr Opin Plant Biol 11:166–170. https://doi.org/10.1016/j.pbi.2008.01.007

McGuire S (2013) WHO, World Food Programme, and International Fund for Agricultural Development. 2012. The State of Food Insecurity in the World 2012. Economic growth is necessary but not sufficient to accelerate reduction of hunger and malnutrition. Rome. FAO. Adv Nutr 4:126–127. https://doi.org/10.3945/an.112.003343

Meena RS, Kumar V, Yadav GS, Mitran T (2018) Response and interactionof Bradyrhizobium japonicum and Arbuscular mycorrhizal fungi in thesoybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Kumar S, Bohra JS, Lal R, Yadav GS, Pandey A (2019) Response of alley cropping-grown sesame to lime and sulphur on yield and available nutrient status in an acidic soil of Eastern India. Energ Ecol Environ 4:65–74. https://doi.org/10.1007/s40974-019-00113-w

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depthand amendments on soil physical and hydrological properties of anAlfisol in Central Ohio, USA. Geoderma 363:1141164

Moraghan JT, Mascagni HJ Jr (1991) Environmental and soil factors affecting micronutrient deficiencies and toxicities. Micronutr Agric 4:371–425

Morrissey J, Guerinot ML (2009) Iron uptake and transport in plants: the good, the bad, and the ionome. Chem Rev 109:4553–4567. https://doi.org/10.1021/cr900112r

Müller O, Krawinkel M (2005) Malnutrition and health in developing countries. CMAJ 173:279–286

Murray CJL, Lopez AD (2013) Measuring the global burden of disease. N Engl J Med 369:448–457

Naderi MR, Danesh-Shahraki A (2013) Nanofertilizers and their roles in sustainable agriculture. Int J Agr Crop Sci 5-19:2229–2232

Naiq KS, Das DK (2008) Relative performance of chelated zinc and zinc sulfate for low land rice. Nutr Cycel Agro Eco 81:219–227

Naqvi S, Zhu C, Farre G, Ramessar K, Bassie L, Breitenbach J, Conesa DP, Ros G, Sandmann G, Capell T, Christou P (2009) Transgenic multivitamin corn through biofortification of endosperm with three vitamins representing three distinct metabolic pathways. Proceedings of the National Academy of Science 106(19):7762–7767

Nazir Q, Hussain A, Imran M, Mahmood S, Ahmad M, Iqbal MM (2016) Zinc biofortification of cereals through fertilizers: Recent advances and future perspectives. Asian J Agri Biol 4:140–152

Nestel P, Bouis HE, Meenakshi JV, Pfeiffer W (2006) Biofortification of staple food crops. J Nutr 136(4):1064–1067

Nouet C, Motte P, Hanikenne M (2011) Chloroplastic and mitochondrial metal homeostasis. Trends Plant Sci 16:395–404. https://doi.org/10.1016/j.tplants.2011.03.005

Noulas C, Tziouvalekas M, Karyotis T (2018) Zinc in soils, water and food crops. J Trace Elem Med Biol 49:252–260. https://doi.org/10.1016/j.jtemb.2018.02.009

Olivares FL, Aguiar NO, Rosa RCC, Canellas LP (2015) Substrate biofortification in combination with foliar sprays of plant growth promoting bacteria and humic substances boosts production of organic tomatoes. Sci Hortic 183:100–108

Ozkutlu F, Torun B, Cakmak I (2006) Effect of zinc humate on growth of soybean and wheat in zinc-deficient calcareous soil. Commun Soil Sci Plant Anal 37:2769–2778

Paine JA, Shipton CA, Chaggar S, Howells RM, Kennedy MJ, Vernon G, Wright SY, Hinchliffe E, Adams JL, Silverstone AL, Drake R (2005) Improving the nutritional value of Golden Rice through increased pro-vitamin A content. Nat Biotechnol 23:482–487

Palmgren MG, Clemens S, Williams LE, Krämer U, Borg S, Schjørring JK, Sanders D (2008) Zinc biofortification of cereals: problems and solutions. Trends Plant Sci 13:464–473. https://doi.org/10.1016/j.tplants.2008.06.005

Panpatte DG, Jhala YK, Shelat HN, Vyas RV (2016) Nanoparticles: the next generation technology for sustainable agriculture. Microb Inoculants Sustain Agric Prod 10:289–300

Panzeri D, Cassani E, Doria E, Tagliabue G, Forti L, Campion B, Bollini R, Brearley CA, Pilu R, Nielse E, Sparvoli F (2011) A defective ABC transporter of the MRP family, responsible for the bean lpa1 mutation, affects the regulation of the phytic acid pathway, reduces seed myo-inositol and alters ABA sensitivity. New Phytol 191:70–83. https://doi.org/10.1111/j.1469-8137.2011.03666.x

Pathak GC, Gupta B, Pandey N (2012) Improving reproductive efficiency of chickpea by foliar application of Zn. Braz Soc Plant Physiol 24(3):173–180

Paul S, Ali N, Datta SK, Datta K (2014) Development of an Iron-enriched High-yieldings Indica Rice Cultivar by Introgression of A High-iron Trait from Transgenic Iron-biofortified Rice. Plant Foods for Human Nutrition 69(3):203–208

Pfeiffer WH, McClafferty B (2007) Harvest plus: breeding crops for better nutrition. Crop Sci 47: S88–S105. https://doi.org/10.2135/cropsci2007.09.0020ipbs

Peleg Z, Saranga Y, Yazici A, Fahima T, Ozturk L, Cakmak I (2008) Grain zinc, iron and protein concentrations and zinc-efficiency in wild emmer wheat under contrasting irrigation regimes. Plant and Soil 306(1–2):57–67

Phattarakul N, Rerkasem B, Li LJ, Wu LH, Zou CQ, Ram H, Sohu VS, Kang BS, Surek H, Kalayci M, Yazici A, Zhang FS, Cakmak I (2012) Biofortification of rice grain with zinc through zinc fertilization in different countries. Plant and Soil 361(1-2):131–141

Pokhrel LR, Dubey B (2013) Evaluation of developmental responses of two crop plants exposed to silver and zinc oxide nanoparticles. Sci Environ 452:321–332

Potrykus I (2001) The golden rice tale. In Vitro Cell Dev Biol Plant 37:93–100

Punshon T, Ricachenevsky FK, Hindt MN, Socha AL, Zuber H (2013) Methodological approaches for using synchrotron X-ray fluorescence (SXRF) imaging as a tool in ionomics: examples from *Arabidopsis thaliana*. Metallomics 5:1133–1145. https://doi.org/10.1039/c3mt00120b

Qadar A (2002) Selecting rice genotypes tolerant to zinc deficiency and sodicity stresses. I. Differences in zinc, iron, manganese, copper, phosphorus concentrations, and phosphorus/zinc ratio in their leaves. J. Plant Nutr 25:457–473

Qaim M (2009) The economics of genetically modified crops. Annu Rev Resour Econ 1:665–694

Rai V, Acharya S, Dye N (2012) Implications of nano biosensors in agriculture. J Biomater Nan Biotechnol 3:315–324

Ram H, Sohu VS, Cakmak I, Singh K, Buttar GS, Sodhi GPS, Gill HS, Bhagat I, Singh P, Dhaliwal SS, Mavi GS (2015) Agronomic fortification of rice and wheat grains with zinc for nutritional security. Curr Sci 109:1171–1176

Ram H, Singh S, Gupta N, Kumar B (2016) In: Singh U, Praharaj CS, Singh SS, Singh NP (eds) Biofortified wheat for mitigating malnutrition BT—biofortification of food crops. Springer, New Delhi, pp 375–385

Ramesh A, Sharma SK, Sharma MP, Yadav N, Joshi OP (2014) Inoculation of zinc solubilizing Bacillus aryabhattai strains for improved growth, mobilization and biofortification of zinc in soybean and wheat cultivated in vertisols of central India. Appl Soil Ecol 73:87–96. https://doi.org/10.1016/j.apsoil.2013.08.009

Raney T (2006) Economic impact of transgenic crops in developing countries. Curr Opin Biotechnol 17(2):174–178

Rawat N, Neelam K, Tiwari VK, Dhaliwal HS (2013) Biofortification of cereals to overcome hidden hunger. Plant Breed 132:5. https://doi.org/10.1111/pbr.12040

Rehman A, Farooq M, Ozturk L, Asif M, Siddique KH (2018) Zinc nutrition in wheat based cropping systems. Plant and Soil 422(1–2):283–315

Rodrigo S, Santamaria O, Chen Y, McGrath SP, Poblaciones MJ (2014) Selenium speciation in malt, wort, and beer made from selenium-biofortified two-rowed barley grain. J Agric Food Chem 62:5948–5953

Rosa L, Cutone A, Lepanto MS, Paesano R, Valenti P (2017) Lactoferrin: a natural glycoprotein involved in iron and inflammatory homeostasis. Int J Mol Sci 18(9):1985

Rose TJ, Impa SM, Rose MT, Pariasca-Tanaka J, Mori A, Heuer S, Johnson-Beebout SE, Wissuwa M (2013) Enhancing phosphorus and zinc acquisition efficiency in rice: a critical review of root traits and their potential utility in rice breeding. Ann Bot 112:331–345. https://doi.org/10.1093/aob/mcs217

Saha S, Chakraborty M, Padhan D, Saha B, Murmu S, Batabyal K, Seth A, Hazra GC, Mandal B, Bell RW (2017) Agronomic biofortification of zinc in rice: Influence of cultivars and zinc application methods on grain yield and zinc bioavailability. Field Crops Res 210:52–60

Saravanan VS, Madhaiyan M, Thangaraju M (2007) Solubilization of zinc compounds by the diazotrophic, plant growth promoting bacterium Gluconacetobacter diazotrophicus. Chemosphere 66:1794–1798. https://doi.org/10.1016/j.chemosphere.2006.07.067

Sazawal S, Black RE, Menon VP, Dinghra P, Caulfield LE, Dhingra U, Bagati A (2001) Zinc supplementation in infants born small for gestational age reduces mortality: A prospective, randomized, controlled trial. Pediatrics 108:1280–1286. https://doi.org/10.1542/peds.108.6.1280

Seyed Sharifi R (2016) Application of biofertilizers and zinc increases yield, nodulation and unsaturated fatty acids of soybean. Zemdirbyste-Agri 103(3):251–258

Shaikh S, Saraf M (2017) Biofortification of Triticum aestivum through the inoculation of zinc solubilizing plant growth promoting rhizobacteria in field experiment. Biocata Agri Biotechnol 9:120–126

Sharma P, Aggarwal P, Kaur A (2017) Biofortification: a new approach to eradicate hidden hunger. Food Rev Int 33:1–21. https://doi.org/10.1080/87559129.2015.1137309

Shen J, Tang C, Rengel Z, Zhang F (2004) Root-induced acidification and excess cation uptake by N2-fixing *Lupinus albus* grown in phosphorus-deficient soil. Plant and Soil 260:69–77

Shivay YS, Kumar D, Prasad R (2008a) Relative efficiency of zinc sulfate and zinc oxide–coated urea in rice–wheat cropping system. Commun Soil Sci Plant Anal 39:1154–1167. https://doi.org/10.1080/00103620801925869

Shivay YS, Prasad R, Rahal A (2008b) Relative efficiency of zinc oxide and zinc sulphate-enriched urea for spring wheat. Nutr Cycl Agroecosyst 82:259–264

Shivay YS, Prasad R, Pal M (2013) Zinc fortification of oat grains through zinc fertilisation. Agric Res 2:375–381. https://doi.org/10.1007/s40003-013-0078-2

Shivay SY, Rajendra P, Rajiv KS, Madan P (2015) Relative efficiency of zinc-coated urea and soil and foliar application of zinc sulphate on yield, nitrogen, phosphorus, potassium, zinc and iron biofortification in grains and uptake by basmati Rice (*Oryza sativa* L.). J Agric Sci 7(2):161–174

Shukla UN, Mishra ML (2018) Biofortification: Golden way to save life from micronutrient deficiency–a review. Agri Rev 39:202–209

Shukla P, Chaurasia P, Younis K, Qadri OS, Faridi SA, Srivastava G (2019) Nanotechnology in sustainable agriculture: studies from seed priming to post-harvest management. Nanotechnol Environ Eng 4(1):11

Shuman LM (2017) Micronutrient fertilizers. Nutr Use Crop Prod 1:165–195

Sihag SK, Singh MK, Meena RS, Naga SR, Bahadur S, Gaurav YRS (2015) Influences of spacing on growth and yield potential of dry direct seeded rice (*Oryza sativa* L.) cultivars. Ecoscan 9 (1–2):517–519

Singla P, Grover K (2017) Biofortified cereal crops: a sustainable approach for food and nutritional security. Curr J Appl Sci Tech 24:1–13

Sperotto RA, Ricachenevsky FK, Waldow Vde A, Fett JP (2012) Iron biofortification in rice: it's a long way to the top. Plant Sci 190:24–39. https://doi.org/10.1016/j.plantsci.2012.03.004

Subramanian KS, Tenshia V, Jayalakshmi K, Ramachandran V (2009) Biochemical changes and zinc fractions in arbuscular mycorrhizal fungus (*Glomus intraradices*) inoculated and uninoculated soils under differential zinc fertilization. Appl Soil Ecol 43:32–39. https://doi.org/10.1016/j.apsoil.2009.05.009

Sultan Y, Walsh R, Monreal CM, DeRosa MC (2009) Preparation of functional aptamer films using layer-by-layer self-assembly. Biom J 10:1149–1154

Takkar PN, Walker C (1993) The distribution and correction of zinc deficiency. In: Robson AD (ed) Zinc in soils and plants. Kluwer Academic Publisher, London, p 51

Tariq M, Hameed S, Malik KA, Hafeez FY (2007) Plant root associated bacteria for zinc immobilization in rice. Pak J Bot 39:245–253

Tesan F, Hernandez F, Torti H, Massot F, Huarte M, RubindeCelis E, Arcos Barreiro ML, Weill R, Cremaschi G, Boccio J, Salgueiro MJ (2011) Glycine-stabilized zinc gluconate has similar bioavailability than zinc sulfate in a zinc fortified probiotic food. Open Nutraceut 4:136–143

Tolay I, Gulmezoglu N (2004) Effect of manganese and zinc foliar application on common bean. Baglar Campus, Eskisehir

United Nations International Children's Emergency Fund (UNICEF) Annual Report (2018). Available at https://www.unicef.org/reports/annual-report-2018. Accessed 20 April 2020

United Nations News (2019). https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html. Accessed 20 April 2020

Wakeel A, Farooq M, Bashir K, Ozturk L (2018) Micronutrient malnutrition and biofortification: recent advances and future perspectives. In: Plant micronutrient use efficiency. Academic Press, London, pp 225–243

Wang S, Yin L, Tanaka H, Tanaka K, Tsujimoto H (2011) Wheat-Aegilops chromosome addition lines showing high iron and zinc contents in grains. Breed Sci 61(189):195

Wang S, Wang Z, Gao Y, Liu L, Yu R, Jin J, Luo L, Hui X, Li F, Li M (2017) EDTA alone enhanced soil zinc availability and winter wheat grain Zn concentration on calcareous soil. Environ Exp Bot 141:19–27

Welch RM, Graham RD (2004) Breeding for micronutrients in staple food crops from a human nutrition perspective. J Exp Bot 55(396):353–364

Wessells KR, Brown KH (2012) Estimating the global prevalence of zinc deficiency: results based on zinc availability in national food supplies and the prevalence of stunting. PLoS One 7:e50568

White PJ, Broadley MR (2005a) Biofortifying crops with essential mineral elements. Trends Plant Sci 10(586):593

White PJ, Broadley MR (2005b) Biofortifying crops with essential mineral elements. Trends Plant Sci 10(12):586–593

White PJ, Broadley MR (2009) Biofortification of crops with seven mineral elements often lacking in human diets - iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytol 182:49–84. https://doi.org/10.1111/j.1469-8137.2008.02738.x

White PJ, Broadley MR (2011) Physiological limits to zinc biofortification of edible crops. Front Plant Sci 2:80. https://doi.org/10.3389/fpls.2011.00080

Whiting SN, de Souza MP, Terry N (2001) Rhizosphere bacteria mobilize Zn for hyperaccumulation by T*hlaspi caerulescens*. Environ Sci Technol 35:3144–3150. https://doi.org/10.1021/es001938v

WHO (2008) In: de Benoist B, McLean E, Egli I, Cogswell M (eds) Worldwide Prevalence of Anaemia 1993–2005: WHO global database on anaemia. World Health Organization Press, Geneva

WHO (2016) Vitamin and Mineral Nutrition Information System World Health Organization

World Health Organization (2000) Turning the tide of malnutrition: responding to the challenge of the 21st century (No. WHO/NHD/00.7). World Health Organization, Geneva

World Health Organization (2002) The world health report 2002: reducing risks, promoting healthy life. World Health Organization, Geneva

World Health Organization (WHO) (2018). Available at https://www.who.int/news-room/fact-sheets/detail/malnutrition

Xu Y, An D, Li H, Xu H (2011) Breeding wheat for enhanced micronutrients. Can J Plant Sci 91:231–237

Yadav GS, Lal R, Meena RS (2020) Vehicular traffic effects on hydraulic properties of a crosby silt loam under a long-term no-till farming in Central Ohio, USA. Soil Tillage Res 202:104654

Yadi R, Dastan S, Esmaeil Y (2012) Role of zinc fertilizer on grain yield and some qualities parameters in Iranian rice genotypes. Ann Bio Res 3(9):4519–4527

Yakoob MY, Theodoratou E, Jabeen A (2011) Preventive zinc supplementation in developing countries: impact on mortality and morbidity due to diarrhea, pneumonia and malaria. BMC Public Health 11(3):S23–S23. https://doi.org/10.1186/1471-2458-11-S3-S23

Yang H, Xu M, Koide RT (2015) Effects of ditch-buried straw return on water percolation, nitrogen leaching and crop yields in a rice-wheat rotation system. J Sci Food Agric 96:1141–1149. https://doi.org/10.1002/jsfa.7196

Ye X, Al-Babili S, Klöti A, Zhang J, Lucca P, Beyer P, Potrykus I (2000) Engineering the provitamin A (β-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. Science 287(5451):303–305

Yruela I (2013) Transition metals in plant photosynthesis. Metallomics 5:1090. https://doi.org/10.1039/c3mt00086a

Yuan L, Wu L, Yang C, Lv Q (2012) Effects of iron and zinc foliar applications on rice plants and their grain accumulation and grain nutritional quality. J Sci Food Agric 93:254–261

Yuan L, Wu L, Yang C, Lv Q (2013) Effects of iron and zinc foliar applications on rice plants and their grain accumulation and grain nutritional quality. J Sci Food Agric 93(2):254–261

Zhang Y, Shi R, Rezaul KM, Zhang F, Zou C (2010) Iron and zinc concentrations in grain and flour of winter wheat as affected by foliar application. J Agric Food Chem 58(23):12268–12274

Zhang YQ, Sun YX, Ye YL, Karim MR, Xue YF, Yan P, Meng QF, Cui ZL, Cakmak I, Zhang FS, Zou CQ (2012) Zinc biofortification of wheat through fertilizer applications in different locations of China. Field Crop Res 125:1–7

Zhao F-J, McGrath SP (2009) Biofortification and phytoremediation. Curr Opin Plant Biol 12:373–380. https://doi.org/10.1016/j.pbi.2009.04.005

Zhu C, Naqvi S, Gomez-Galera S, Pelacho AM, Capell T, Christou P (2007) Transgenic strategies for the nutritional enhancement of plants. Trends Plant Sci 12:548–555

Zou CQ, Zhang YQ, Rashid A, Ram H, Savasli E, Arisoy RZ, Ortiz-Monasterio I, Simunji S, Wang ZH, Sohu V, Hassan M (2012) Biofortification of wheat with zinc through zinc fertilization in seven countries. Plant and Soil 361(1–2):119–130

Resources Management for Sustainable Sugarcane Production

18

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Contents

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Abstract

Globally, sugarcane is cultivated, ranging from warm temperate regions to the humid tropics. The judicious uses of fertilizers are advocated for proper nourishment of canes, which varied following the global divergent inherent fertility status, soil texturally class, and different agro-climatic conditions. Inherent soil fertility status and application of different nutrients through fertilizers, both affect the cane productivity to a significant extent. Therefore, the sugarcane yields get affected not only by deficiencies but even by an excess of macro but micronutrients; as excess amounts promote lodging, insect-pest attack, and environment complication, while the lesser amounts adversely affect cane yields. However, their interactions further complicated the role of a single nutrient. Present compilation/chapter considers the global fertilization trends in sugarcane using existed data to delineate the importance of proper fertilization on cane quantity and quality. Further, the use of organic amendments viz. farmyard manures and microorganisms viz. azotobacter needs to be counted. More than ever before, there is a need for knowing the inherent fertility of soils, soil textural class, agro-climatic conditions, preferred sugarcane cultivars, etc. for finalizing fertilizer doses as under and above fertilization leads to poor recovery. Hence, balanced and integrated nutrient fertilization is a must-win global technology for improving both qualities as well as the quantity of the so produced sugarcanes, which further improved the profits of the cane farmers.

Keywords

Fertilizers · Nutrients · Quality · Resource use efficiency · Sugarcane · Yields

Abbreviations

Al	Aluminum
$AlPO_4$	Aluminum phosphate
B	Boron
Ca	Calcium
Cl	Chloride
cm	Centimeter
CO_2	Carbon dioxide
Cu	Copper
EC	Electrical conductivity
Fe	Iron
FYM	Farmyard manure
g	Grams
$H_2PO_4^-$	Dihydrogen phosphate
ha	Hectare
HPO_4^{2-}	Monohydrogen phosphate
INM	Integrated nutrient management
IW/CPE	Irrigation water to cumulative pan evaporation ratio
K	Potassium
kg	Kilograms
l	Liters
m	Meter
Mg	Magnesium
mg	Milligrams
MJ	Mega joules
mm	Millimeter
Mn	Manganese
Mo	Molybdenum
Mt	Million tons
N	Nitrogen
Na	Sodium
NUE	Nitrogen use efficiency
P	Phosphorus
PAU	Punjab Agricultural University
RDF	Recommended dose of fertilizers
S	Sulfur
SOC	Soil organic carbon
SOM	Soil organic matter
t	Tons
Zn	Zinc

18.1 Introduction

Sugarcane belongs to the genus *Saccharum*, family *Gramineae* (*Poaceae*), class monocotyledons, order *Glumaceae* subfamily *Panicoidae*, tribe *Andripogoneae*, and sub-tribe *Saccharininea*. It is a grass, which stores energy in stalks as sucrose (sugar), rather than in seed heads as starch. The archetypal sweet "noble canes" evolve from its relatives (wild) in Papua New Guinea. Three close relatives *viz. Saccharum spontaneum* (very vigorous), *S. robustum* (heavier stalked), and *S. edule* (with edible flower) also establish in Papua New Guinea with low Brix and higher fiber content. Natural hybrids between *S. spontaneum* and *S. officinarum* responsible for *S. sinense* and *S. barberi*, which were widely cultivated in India and China (Bull 2000) (Fig. 18.1). Initially, sugarcane used for chewing, but in the Indus Valley around three thousand years ago, the preparation of crystallized sugar from cane stalk was reported. However, in the Indian sub-continent, sugarcane reported being a vital crop by around 327 B.C. In 647 and 755 A.D., it was introduced to Egypt and Spain, respectively, and hence nearly to all tropical and subtropical regions, through traders (Malavolta 1994). Globally, modern varieties are more vigorous, high nutrient demanding, high yielding and disease-pest resistant than the old noble canes. Balanced fertilization as per inherent soil fertility, agro-climatic conditions, soil textural class, organic matter status are the pillars for profitable farming. For knowing the inherent soil fertility, scientific soil sampling and testing played a key role (Bhatt and Sharma 2013). Generally, modern sugar industries aimed at

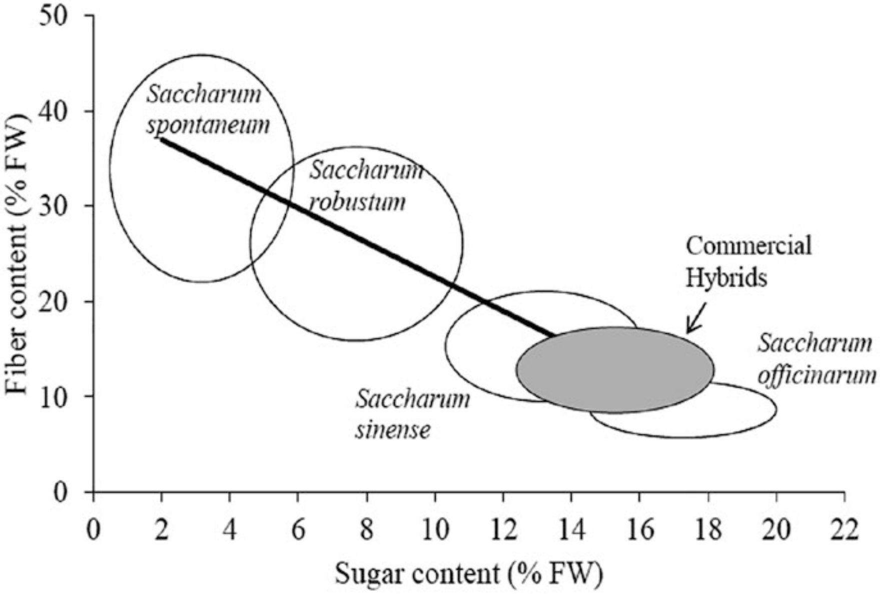


Fig. 18.1 Progressive change in fiber and sugar levels from wild to noble canes (Adopted, Bull 2000)

maximum sugar production without considering the fertilization aspect. Farmers generally tend to apply nutrients on the higher side, which is certainly not required as in the long run it has its adverse consequences. Many countries have developed successful cane fertilization programs for profitable cane farming and advocated their farmers for their particular conditions.

It was also supposed that northeastern Indian moist parts were responsible for the evolution of thinner Indian canes as some plants closely related to *S. spontaneum* (Barber 1931).

18.1.1 Global Prospective of Sugarcane Production

From the last two decades, particularly in South America, Asia, and Africa, the sugarcane industry has continued to expand. As per one estimate, sugarcane cultivated area throughout the globe increased to 39.2% from 1990 to 2010 (FAO 2012) (Fig. 18.2), while the productivity jumped from 1052 million tons (Mt) to 1685 Mt during the same tenure. Maximum per cent increase in the area; yield and production reported from South America from 1990 to 2018 as of 116, 16.2, and 151.2%, respectively (http://www.fao.org/faostat/en/#data/QC), while the reduction in cane area reported in America (N.C), reduction in yield reported in Africa with least production in America (NC) (Fig. 18.2). South America, followed by Asia, North, and Central America, and Africa, are the major cane growing regions. Brazil

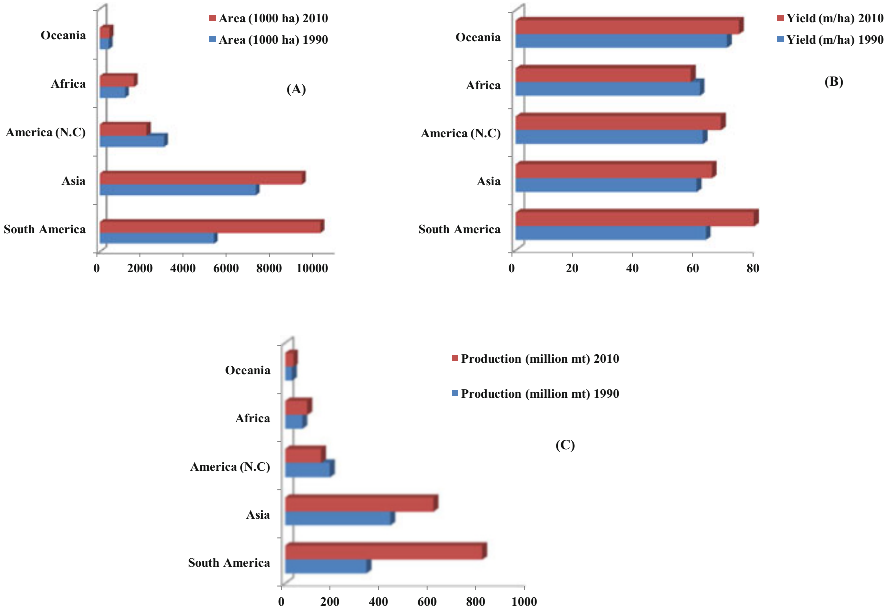


Fig. 18.2 Sugarcane area, yields, and production from 1990 to 2010 at the global level (Modified, FAO 2012)

is dominating world sugar exports followed by Thailand and Australia (FAO 2020). Ethanol production from sugarcane, as a replacement for petroleum products, is the new diversion, most notably in Brazil, where around half of the produced canes used for this purpose. Ethanol production followed by power generation from sugarcane bagasse is also adopted in most of the countries.

18.1.2 Sugar Accumulation

In sugarcane, the C_4 pathway of photosynthesis is followed in which normal leaf anatomy adopted by plant, with the vascular bundles surrounded on the inner layer by bundle sheath cells (contain starch-rich chloroplasts) and on the outer layer by mesophyll cells. In the mesophyll cells, carbon dioxide (CO_2) converts to malate through oxaloacetate, which undergoes decarboxylation to CO_2 (which enters the Calvin cycle to produce carbohydrates) and pyruvate (which returned to mesophyll). Sugarcane (C_4 plant) differs from C_3 plants, where CO_2 is fixed as 3-phosphoglycerate. The major end product of carbohydrate production in sugarcane is sucrose rather than starch, which transported from the leaves to the stalk through xylem and phloem (Hartt et al. 1963). For converting solar light energy into chemical energy, sugarcane is considered to be an efficient plant.

18.1.3 Sugarcane in India

In India, sugarcane is an important cash crop, and second-largest agro-based industry after textile industry with a total cultivated area of 47.3 lakh hectare (ha) and 3769 lakh tons of yearly production, which employs too many engaged in cane cultivation and its industry (FAO 2020). During the years 2017–2018, it shared around 35.14% of the total value of agriculture production (FAO 2020). Per serving of sugarcane juice (28.35 grams—g) contain 111.13 kilo Jules (kJ) (26.56 kcal—kilo calorie) of energy, 27.51 g of carbohydrates, 0.27 g of protein, 11.23 milligrams—mg (1%) of calcium (Ca), 0.37 mg (3%) of iron (Fe), 41.96 mg (1%) of potassium (K), and 17.01 mg (1%) of sodium (Na) (Nutrient Information from ESHA Research) so quite useful for the human nutrition.

Juice's sugars and non-sugars can indicate the quality of the juice in sugarcane. High sucrose, high purity, low fiber, and low non-sugars are some characteristics of canes for the high recovery of sugar. Crystal shape, reducing sugar levels, color, and filterability are differential quality parameters of the canes, while other factors which could involve in deciding the sugar contents are a selection of proper varieties, adopted harvested practices, delays in the harvest to crush, disease and pest attack, and integrated soil test based fertilization are imperative factors affecting juice quality (Wood 1982; Xiao et al. 2017). Chemical class of cane juice like sucrose content and non-sucrose parameters that can affect sugar recovery in the processing stream can directly be impacted by the soil textural class and fertilizer management (Wood 1982). In this review, stress being rewarded to the balanced use of different nutrients viz. nitrogen (N), phosphorus (P), and K for improving cane quality so produced.

18.1.4 Sugar Production Process

Sugarcane (80%) or sugar beet (20%) principally used for the production of white sugar, *Khandsari,* and Jaggery. In India, white sugar is extracted from sugarcane while in Punjab, India one private mill Rana Sugars Ltd., Buttar Seviyan also attempted to produce the sugar from the sugar beet too. In the sugar industry during the extraction process, several by-products viz. Molasses, Bagasse, and Press mud produced which further have their values and thereby can also be sold (Fig. 18.3).

The sugarcane juice is further processed to get sugar and Molasses, which can either be sold directly or further processed in the distillery industry (Fig. 18.3) for production of either industrial alcohol (sold to Chemical companies for industrial consumption) or as potable alcohol (liquor); or used for blending in the fuel like ethanol. Generally, 1000 kilograms (kg) of sugarcane provides us 95 kg of sugar and 10.8 liters (l) of ethanol, ~300 kg of bagasse from which power of around ~130 KWh (kilowatt-hour) can be produced (Source: alpha_invesco_sugar_industry.pdf).

18.2 Sugarcane and Its Nutrient Requirements

Sugarcane required only 17 elements for proper growth and productivity and is composed of minerals, water, and organic materials. Around 95% of fresh weight of sugarcane plant composed of carbon, hydrogen, and oxygen, (which are structural elements), while 5% composed from mineral components that are required for proper growth and reproductive cycle (de Souza et al. 2015). Nitrogen, P, and K

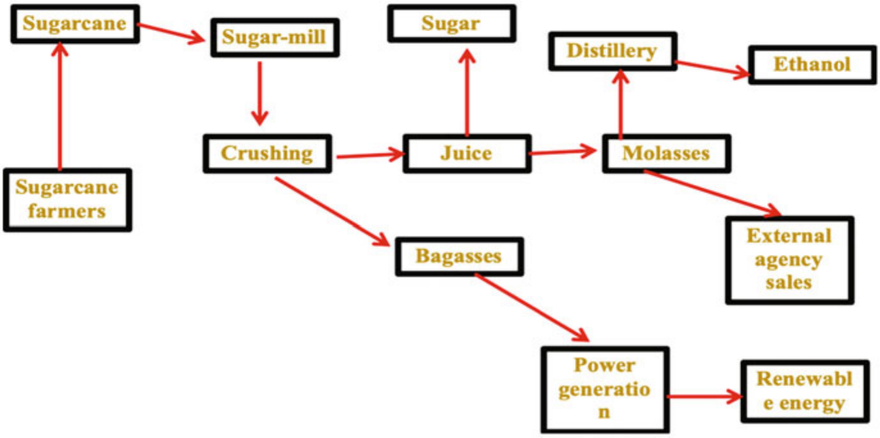
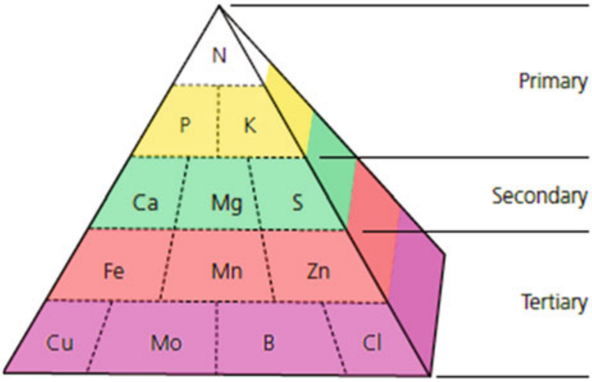


Fig. 18.3 By-products of sugar industries

Fig. 18.4 General essential plant nutrients (Adopted, Arnon and Stout 1939)



(primary nutrients), and Ca, magnesium (Mg) and sulfur (S) are (secondary nutrients) required in relatively more copious amounts, thus known as macronutrients (Fig. 18.4), while zinc (Zn), copper (Cu), Fe, manganese (Mn), boron (B), chloride (Cl), and molybdenum (Mo) (part of a tertiary group) require in relatively small amounts are termed as micronutrients.

Micronutrients, though required in small amounts, but equally important as usually taken up in part per million (ppm), and deficiency of any one of them will cause significant losses in cane yields as well as quality. Silicon is the 14th element that has received widespread attention in recent years as far as sugarcane nutrition is concerned, as it is accumulated in large amounts in sugarcane and further helps to get better yields (Kingston 1999; Meyer et al. 1999; Berthelsen et al. 2001). Nutrient requirement of sugarcane varied under different countries, which further depends upon the several factors viz. soil textural class, cane cultivars, agro-climatic conditions, and adopted indigenous technical knowledge (Table 18.1).

18.3 Principles Pertaining to Sugarcane Nutrition

As and when nutrient supply increased through fertilizers, the cane yields directly increases, but with time this increases but with the decreasing rates. Therefore, there is a need to delineate the dose of different fertilizers at which yields increased at the top with increasing trends, and there should be a check beyond that dose, which is also economical for the farmers. This statement is already supported by a prestigious law known as "*Law of Diminishing Returns*" (Mitscherlich 1909). The reason for the lower demand of micronutrients is their higher use efficiency by the plants to have optimum cane productivity with desired quality; thereby, their yield curve tends to have the steepest slope concerning macronutrients. Therefore, optimum supply of the different nutrients which further varied as per the type of soil texture, agro-climatic conditions, cultivars selected for cultivation, inherent soil fertility, management practices, etc. are must-win factors for having potential yields while on another side higher amounts of nutrients promoted the vegetative growth and attack of

Table 18.1 Comparative nutrients removal rates by sugarcane in different countries (Adapted from Kingston 1999)

	Macronutrients (kg t^{-1})						
Country	N	P	K	Mg	Ca	S	Source
Hawati	1.13	0.29	2.22	0.35	0.43	–	Humbert (1968)
India	1.20	0.20	1. 19	–	–	–	Verma et al. (2014)
South-Africa	1.35	0.16	3.26	0.39	0.42	–	Thompson (1988)
Brazil	0.80	0.132	1.10	0.30	0.3	0.25	Malavolta (1974)
Australia	1.30	0.18	2.23	0.22	0.29	0.36	Kingston (1999)
Average	1.16	0.19	2.00	0.31	0.36	0.31	
	Micronutrients (g t^{-1})						
	Fe	Mn	Zn	Cu	B	Mo	
Brazil	31	11	4.5	2.0	2.0	0.01	Malavolta (1974)
Australia	78	42	4.95	0.75	–	–	Kingston (1999)
South-Africa	–	11	2.5	0.5	1.2	–	Thompson (1988)

insect-pest and diseases, and thus finally reduce the quality and quantity of the sugarcane produced. Therefore, optimum/balanced fertilization neither higher nor lower side only the answer for the judicious use of the fertilizers in sugarcane.

18.4 Nutrient Uptake in Sugarcane viz-a-viz Climatic Conditions

Climatic conditions are an essential factor for deciding the nutrient requirements of the sugarcane. The drier weather conditions with low humidity, bright sunshine hours, cooler nights with wide diurnal variations, and very little rainfall during ripening period are some required weather factors for having decent Brix and cane yields. Being a “Tropical plant,” sugarcane is grown from latitude 36.7°N and 31.0°S, from sea level to 1 kilometer (km) of altitude. Being a long duration crop worth from 10 to 12 months, it faces all the seasons equipped with different rainfalls and temperatures during its life cycle. Around 6350 mega joule (MJ) m^{-2} of total radiations are received yearly by whole cane crop, out of which the canopy intercepted about 60% of the radiation. Further, Ramanujam and Venkataramana (1999) delineate a good co-relation ($R_2 = 0.913$) between intercepted active solar radiations and yields. In sugarcane, a rough estimate delineates that sunlight, wind, and air temperature will be responsible for water loss in terms of 80, 14, and 6%, respectively, which must be cut and diverted to transpiration for overall having higher production (Chauhan 2019). Further, high-speed winds cause lodging and cane breakage. In general, the following climatic variables affect sugarcane.

18.4.1 Rainfall

For sugarcane crop, annually, a total rainfall between 1100 and 1500 millimeter (mm) with proper distribution is adequate. It may be abundant in the months of vegetative growth. Rapid cane growth, cane elongation, and internode formation encouraged by rainfall more particularly during the period of active growth while reciprocate are true for the ripening phase as higher rains results in poor juice quality, higher vegetative growth, the formation of water shoots, increase in the tissue moisture, and also affect the harvesting and transport operations in regions of heavy textured soils.

18.4.2 Temperature

Optimum temperature for sprouting (germination) of stem cuttings is 32–38 °C, while at ripening 12–14 °C is desirable as at higher temperatures reversion of sucrose into fructose and glucose may occur, which reduces overall quality. The germination get slows down below 25 °C, reaches plateau between 30 and 34 °C, reduced above 35 °C, and stopped above 38 °C. The temperatures above 38 °C reduce the photosynthesis rates.

18.4.3 Relative Humidity

High humidity (80–85%), particularly during the grand growth stage, favors the rapid cane elongation. A moderate value of 45–65% during the ripening phase, coupled with limited water supply, is favorable for potential yields.

18.4.4 Sunlight

Sugarcane being “a sun-loving plant,” grow well in areas receiving solar energy from 18 to 36 MJ m^{-2}. Further, as a C_4 plant, sugarcane is capable of preparing its food with high photosynthetic rates. Long duration high-intensity sunrays promote tillering while cloudy and short days harm the overall performance of sugarcane. Further, it was delineated that during the day time of 10–14 h, stalk growth increases (Ramanujam and Venkataramana 1999).

18.5 Factors Affecting Nutrient Supply

18.5.1 Soil Organic Matter

The SOM is the single most crucial parameter for deciding the quality of soil/land selected for sugarcane cultivation which broadly comprised varying degree of decomposition of roots, leaves, microorganisms, and animal remains, comprise mainly of polysaccharides to the stabilized organic humus fractions (made up of mainly humic and fulvic acids). Generally, in the soil, as compared to sand, SOM present in significantly lesser quantities. Soil organic matter improves the physico-chemical properties of soil by having its effect on soil structure and tilth, cation exchange capacity and buffering capacity, the supply of NPK reduces erosion, soil water holding capacity, and resistance to compaction, encouraging the build-up of soil microorganisms (Parsons 1962; Jangir et al. 2019). Further, SOM may be estimated from the soil organic carbon (SOC) by multiplying later with conversation factor 1.724 (Pribyl 2010; Meena et al. 2016a, b, 2016a, b; Varma et al. 2017).

18.5.2 Soil pH

Soil pH indicates its extent of variation from the normal limits. Generally, a soil with a pH range of 6.5–8.5 found to be suitable for cultivation of different crops (PAU 2018-2019). In acidic soils, hydrogen and aluminum (Al) ions predominate over hydroxyl ions while in alkaline soils reverse the situation (Kumar et al. 2017a, b; Meena et al. 2019a, b). The scale is logarithmic since a change of 1 unit on the scale represents a tenfold change in acidity (Wiley 2018). Further, soil pH controls the solubility and availability of nutrients to the plant from the soil solution. Increased acidity (pH <7) causes the reduction in the availability of essential nutrients such as N, P, K, Ca, Mg, and S while micronutrients such as Cu and Zn become more available (Fig. 18.5). Under the acidic conditions below a pH 5.3, Al becomes soluble and is toxic for root growth, especially for legume crops that may be used in rotation with sugarcane as most cultivars of sugarcane tend to be tolerant of high levels of Al (Hetherington et al. 1986). However, at high pH above pH >8.5, the availability of all micronutrients except Mo gets reduced. Therefore, the most favorable pH of 6.5–8.5 delineates the best range for the availability of all the required nutrients to the sugarcane crop (PAU 2018-2019). Hence, for having improved yield as well as quality, the pH range must be managed either through lime or gypsum on the soil test basis. In Punjab, Punjab Agricultural University (PAU), Ludhiana, Punjab, India already recommended CoJ-88 for the salt-stressed conditions to the target regions.

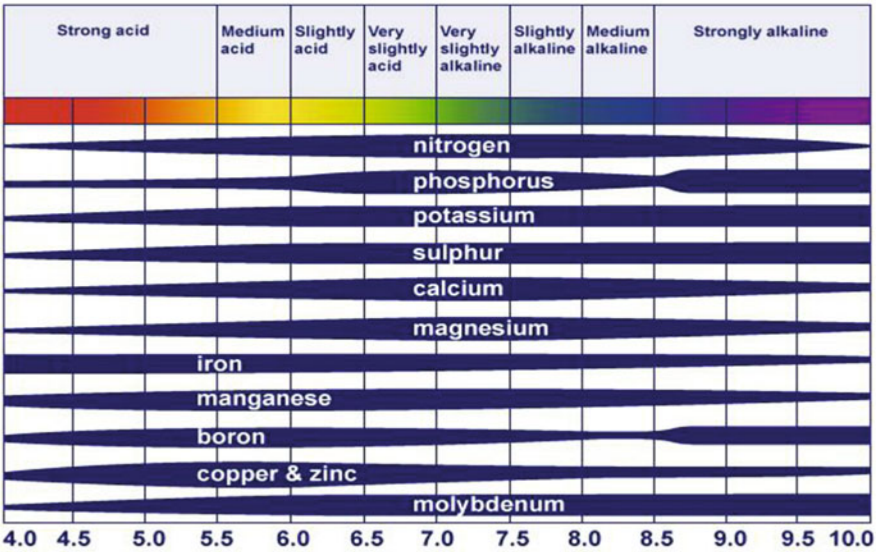


Fig. 18.5 Nutrient availability viz-a-viz pH fluctuation (Adopted, Truog 1948)

18.5.3 Nutrient Movement Pathways in Soils

Mostly, nutrients move from the soil solution to the plant through roots under the following two processes:

1. *Mass flow*: Under this pathway, nutrients moved by the convective flow from the soil solution to the plant roots with irrigation water. Higher the rate of water entered in the plant root through soil solution against the transpiration pull, higher the nutrients will enter the plant roots, which are further related to higher yields. Nitrogen and P (with a net negative charge) moved directly to the roots mainly by mass flow as they are not attached to the soil clay (Meyer 2013).
2. *Diffusion*: Here, under the diffusion pathway, in soil solution, nutrient ions are transported to the roots from a higher to a lower concentration with a random or thermal action (Meyer 2013). Now as and when nutrients are taken up by plant roots, then a concentration gradient is created, which further resulted in the nutrients movements from the soil solutions to the plant's roots. The depleted solution is replenished by nutrients that diffuse through the soil water from areas of higher concentration. For example, K is moved from the illite minerals to soil solution and then from the soil solution to the plant roots under this pathway (Meyer 2013).

18.5.4 Inherent Soil Nutrients and Effects on Soil Fertilization

An idea regarding the inherent nutrient supplying capacity of the soils is very important before scheduling the fertilization for any crop, as all the crops required nutrients in definite amounts, while on the other way, soils also supplied all the nutrients depending upon their fertility levels. The objective of knowing soil's inherent capacity through soil testing is to fulfil this gap (Bhatt and Singh 2020a, b). With soil testing**,** inherent nutrient supplying capacity of soils about both Physico-chemical properties viz. soil pH, electrical conductivity (EC), and SOC (%) and macronutrients viz. available P and K, and micronutrients viz. available Zn, Cu, Fe, and Mn affect growth as well as the rate of fertilization significantly as after knowing it, one could decide the rate of different fertilizers to saturate the soil solution. Soil inherent fertility maps using geological positioning system (GPS) prepared for Regional Research Station, Kapurthala both for macro as well as (Figs. 18.6 and 18.7) for the judicious use of the fertilizers in the sugarcane crop. In the figures, A, B, C, D, E, F, G, and H represent the different blocks of the Research Farm, where fertilization generally did for the sugarcane research and seed production programme.

Figure 18.6 indicated that the soil pH prevails typically in the range except for the B and D blocks, which could be improved with the green manuring while spots in E,

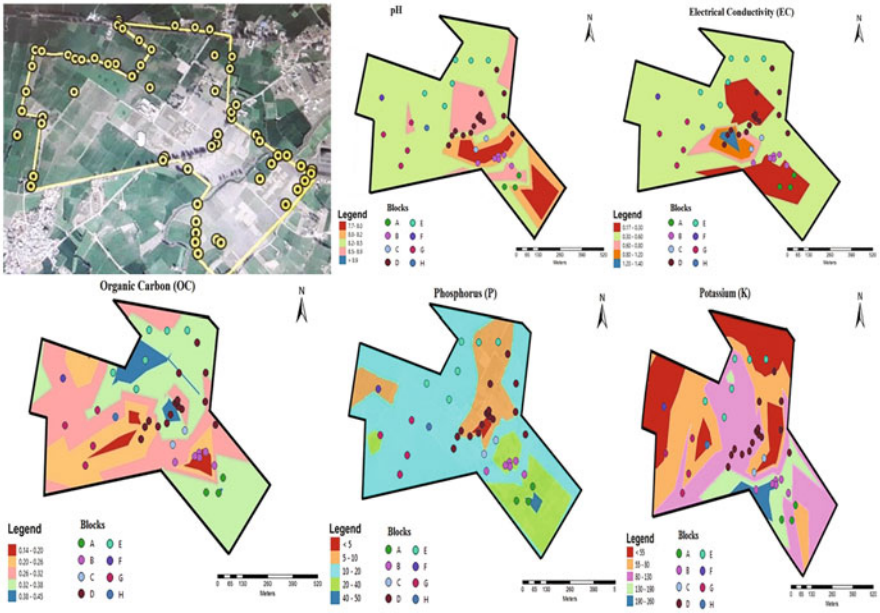


Fig. 18.6 Macronutrients (mg kg^{-1}) soil fertility map of RRS, Kapurthala, Punjab, India

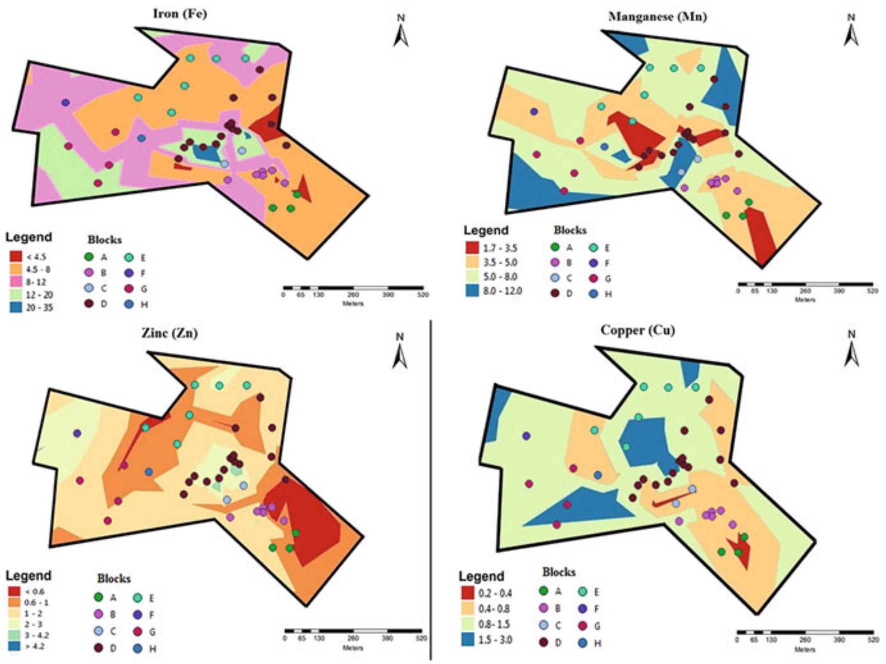


Fig. 18.7 Micronutrients (mg kg^{-1}) soil fertility maps of RRS, Kapurthala, Punjab, India

G, and H are there, which needs immediate reclamation using gypsum. However, A, C, D, and E blocks have higher spotic salt concentration. As per as organic carbon (%) concerned, it was observed that only A, D, and E blocks showing medium range, while all other blocks reported with lower range demanding 25% higher N-fertilization. Only D showed a lesser range of P while spotic deficiency also observed in all the blocks. As per K, deficiency observed in some blocks viz. B, E, and H blocks. However, as far as micronutrients status in the farm is concerned, it was delineated that Zn reported being deficient throughout the farm, Fe reported to be higher in all the blocks while lower in B, D, and C blocks.

Manganese observed to have deficient pockets in all the blocks except G and H block, while Cu observed in the higher range in all the blocks (Fig. 18.7). Based on these digital fertility maps, it becomes quite easy to schedule the fertilization of both macro and micronutrients. However, further, more detailed soil sample analysis will provide us more-clear picture regarding the spatial distribution of these nutrients (Bhatt and Singh 2020a).

18.6 Sugarcane Fertilization and Factors Affecting

18.6.1 Nitrogen

Nitrogen plays a crucial role in improving both quantities as well as quality parameters of the sugarcane crop. Establishing an economic balance for judicious N-fertilizers for desired yields is critical. The object to use higher doses of N-fertilizers is to improve vegetative growth, but rapid growth due to higher levels of N, moisture instead reduces the quality of the produced canes. Generally, excess of N-fertilization reduces the fiber contents. In the absence of any N-fertilization, soils have the inherent supply of N through the mineralization of SOM (covered a wide range from <70 to >140 kg N ha^{-1}) (Meyer et al. 1986). Fortunately, the recommendations for N by PAU matched the N mineralization potential of soils more particularly for the medium fertile soils. Thereby reducing the risk of over-applying N which might result in lodging which further declines recoverable sucrose invites higher infestation and insect-pest attack. In a two-year field study, in India, a significant increase in organic non-sugars was observed. However, in the same experiment, finally, it was reduced with a hike in total amino acid, and phenol content, while reduction of colloid and gum content due to the dilution effect of inorganic non-sugars (Asokan and Raj 1984).

Many studies that evaluate fertilization with macronutrients, especially N showed a high correlation between the number of stems and yield of sugarcane (Vale et al. 2012). Knowing the crop requirements for N, however, is not the same as knowing how much fertilizer N to apply, but we have to enquire regarding the inherent soil fertility, and then only difference will be applied through the fertilizers.

In the literature, several studies reported declined trends of sugar content at a higher rate of N-fertilization which not only confirms the need to reduce rates but also allays fears that N deficiencies might occur at the lower rates. However, the global recommendation for N fertilization for sugarcane varied a lot depending upon the response received in terms of yields and soil properties (Srivastava and Suarez 1992). Ratoon sugarcane crop is always more sensitive to N-fertilization than the seed crop (de Geus 1973; Vuyyuru et al. 2019). Different countries of the world utilize different N-fertilizer recommendations for sugar industries (Table 18.2).

The experiments conducted at PAU (2018-2019) in Punjab, India, stated that higher N-doses are required to the ratoon crop due to already well-established roots. However, running on the same path, PAU has already recommended higher N-dose for the ratoon crop (488 kg urea ha^{-1}) than the seed crop (325 urea ha^{-1}) in the Punjab region of India for medium fertile soils having SOC between 0.4 and 0.75% (PAU 2018-2019). Further soils having lesser SOC ($<0.4\%$), the application of 25% higher urea is recommended, while for soils having SOC greater than 0.75%, the recommendation with 25% lesser dose of urea was carried out (PAU 2018-2019). Sugarcane nutrient studies carried out by Rozeff (1990) from southern Texas has recommended 56 and 90 kg N ha^{-1} for the plant cane crop after a fallow rotation and for the successive crop rotation. As a thumb rule, 1 kg N t^{-1} cane required for the plant while 1.25–1.50 kg N t^{-1} cane required for ratoon crops, thereby later crop

Table 18.2 General nitrogen fertilizer recommendations for sugar industries in different countries

Country	Inherent Organic matter	N mineralizing capacity	N-application (kg ha^{-1})		Remarks
			Plant	Ratoon	
Hawai	General	–	224	224	In drip irrigation as splits
India	General	–	50–100	150–200	For smallholder grown cane rate lower
South Africa (Meyer et al. 1986)	<2 2–4[a] 2–4[b] >4	Low Moderate High Very high	120–140 100–120 80 60	160–200 140–160 120 100	The rate depends on water-stressed conditions viz. rainfed or irrigated.
Florida	Sandy OM < 35% OM 35–85% OM > 85%	Low Moderate Very high Very high	200 120 34 0	200 120 34 0	Sandy soils, split applications Sandy muck soils Mucky sand soils Muck soils
Australia	<0.7 0.7–1.4 1.4–2.1 2.1–2.8 2.8–3.5 3.5–4.2 > 4.2	Very Low Low Moderately Low Moderate High High Very high	140 130 120 110 100 90 80	160 150 140 130 120 1100	Under legumes, N fertilization rates must be reduced

[a] Refers to non-red soils
[b] Refer to mainly to deep red soils

required a minimum of 25% higher N-dose because of the prior well-developed root system (Meyer 2013).

In South Africa, for each successive ratoon crop, the dose of N fertilizer increased, which may vary from 50 to 150 kg N ha^{-1} year^{-1}. However, the current N dose varied from 120 to 150 kg and 16–200 kg N ha^{-1} for plant and ratoon crops, respectively (Canegrowers 2002). In Punjab, India, for plant crop 150 kg N ha^{-1} while for ratoon crops 225 kg N ha^{-1} is recommended for the medium fertile soils having SOC content between 0.4 and 0.75%, as ratoon crop required higher doses of N-fertilizers. Further, soils having lesser than 0.4% advocated for 25% higher, while soils having SOC >0.75% advocated for 25% lesser dose. Moreover, as an application of farmyard manures (FYM) at 20 t ha^{-1} is also recommended for this region, and accordingly, N dose reduced from 150 kg ha^{-1} to 100 kg ha^{-1} (PAU 2018-2019).

Obreza et al. (1998) reported significantly higher sugarcane yield on light-textured soils under splits applications compared to the application of the same amount of N without splitting. According to Rice et al. (2002), the nutritional requirement for sugarcane growing on differently textured soils viz. sandy, mucky sandy, and sandy muck soils varied, and are more recommendation for a soil having a greater proportion of sand. Glaz and Ulloa (1995) delineated that if the last N application was completed on a 12- or 18-month crop by the fourth or sixth month, sugarcane production would be higher. Furthermore, Samuels (1969) reported higher doses of N fertilizers required in the early stages of growth viz. germination. Wood (1964) and De Geus (1973) observed a decline in the production of sugarcane from seed to ratoon onwards due to a decline in inherent soil fertility.

18.6.1.1 Effect of Nitrogen on the Cane Quality

Nitrogen must be added in the soil for improving N status of the soil solution from where plant roots could easily extract it for carrying out all the proper metabolic activities viz. photosynthesis, meristematic activities *viz.* vegetative growth and tillering (Vuyyuru et al. 2019). Sugarcane could store the N for its future use in case of any emergency. However, lodging might be caused under the higher doses along with delayed maturity, reduced sucrose levels, and higher susceptibility towards insect-pest attack. Throughout the globe, scientists are engaged working out the judicious use of fertilizers and in finding out its placement for overall improving the declining N-use efficiency. In this regard, already leaf color chart, soil plant analysis development (SPAD), etc. working very well in the farmer's fields. The PAU recommended the use of leaf color chart (LCC) for the N management in cereals to the Punjab State (PAU 2018-2019).

18.6.1.2 Nitrogen Use Efficiency

Nitrogen use efficiency is an index to determine the efficiency of N usage by the plants as leftover either lost to the atmosphere or to the underground water table (Meena et al. 2016a; Kakraliya et al. 2017a, b; Sharma et al. 2019). Lower NUE led to higher cost of cultivation, global warming, groundwater pollution, but its range varies with soil textural class, agro-climatic conditions, cropping intensity, implemented conservation practices, and available K content. Table 18.3 delineates the varied range of NUE in different countries.

Sugarcane crop desired higher NUE as lower NUE apart from affecting sugar quality, can potentially have considerable ecological significance (Keating et al. 1997), leaching losses of N in sandy soils (Thorburn et al. 2003), affected water body qualities (Bramely et al. 1996), and accelerate greenhouse gas emissions through denitrification (Keating et al. 1997; Haynes and Hamilton 1999). Further,

Table 18.3 Range of nitrogen use efficiency in different countries

Country	NUE (%)	Scientist
Australia	24–41	Keating et al. (1996)
Florida	30–42	Gascho (1983)
South Africa	27–36	Wood (1972)
Guadeloupe	6.1–34	Kingston (1999)

Keating et al. (1996) reported higher nitrate levels in sampled 2% boreholes in Australia (>50 mg l^{-1}), which is a severe situation for human health, and ecological balance.

18.6.1.3 Sugarcane Nitrogen Requirements

Sugarcane N-requirement varied as per varying clay percentage in soils and with climatic conditions. Even though there are some other important factors which need to be discussed here for more clarity of the nutrient requirements.

Crop Stage and Cycle

Throughout the globe, cane planted crops showed lesser yield response than ratoon crop as the former crop requires about 40 kg lesser N ha^{-1}, which is because of other minerals N, being produced during intervening periods. Both the age of cane and season significantly responsible for N uptake variations (Thompson 1988). Up to 80 and 10% of accumulated N could be used up after four months, under favorable and unfavorable cycle, respectively. Fertigation in South Africa on an unfavorable cycle delineated to be more effective than conventional broadcasting for cane grown, unlike during the favorable cycle (Weigel et al. 2008).

Age of Crop

Longer the summer seasons, more will be mineralization of N, showing further higher N-use efficiency and lesser requirements of the N-fertilizers for cane development. In South Africa, sugarcane crop, experiencing two summer season showing higher yields than the crop facing single summer season. In Punjab, generally, there are two cycles viz. October-November (Autumn cane) and February-March (Spring canes) and average cane duration in 10–12 months (PAU 2018-2019). As per the age of canes, different quantities of nutrients get accumulates in its vegetative portion (Table 18.4).

Soil Nitrogen Mineralization Potential

Nitrogen mineralization potential of the soils varied with ecological factors viz. rainfall patterns, inherent soil fertility, which further collectively decides the total N requirements of the canes. Mineralization (of organic N to ammonium) followed by the nitrification (ammonium to nitrate) is an uninterrupted process (Fig. 18.8), but

Table 18.4 Nutrient uptake comparisons in sugarcane crop at 4 and 6[a] (Adapted, Thompson 1991)

	Spring start in % of total uptake		Autumn start in % of total uptake	
Element	At 4[a]	At 6[a]	At 4[a]	At 6[a]
N	82	99	12	24
P	66	90	13	33
K	60	82	7	25
Ca	57	85	6	17
Mg	78	95	8	24

[a] Months

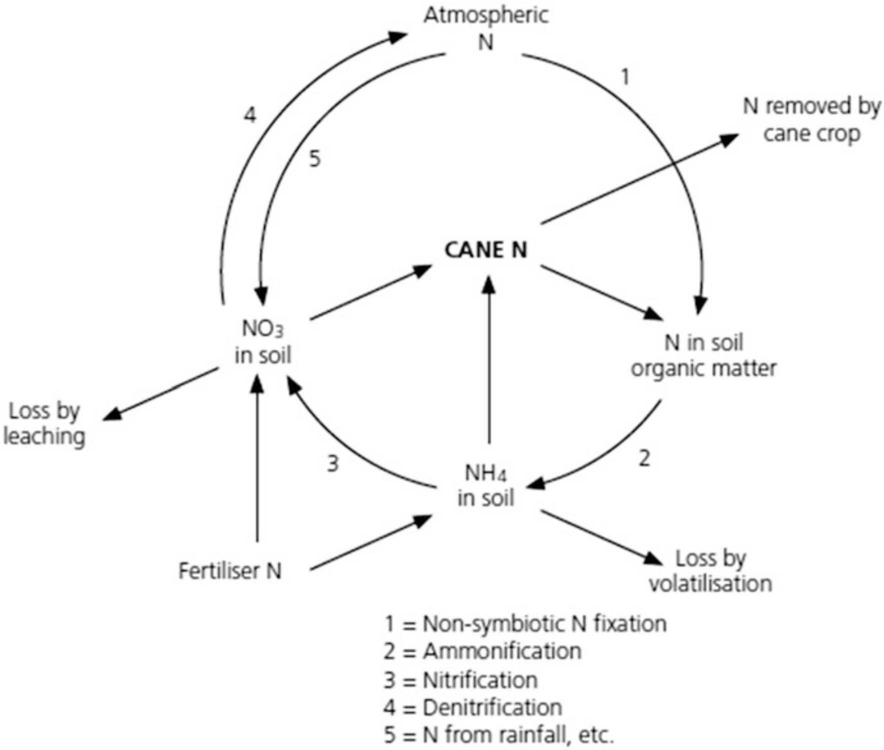


Fig. 18.8 N-transformations in soils receiving fertilizers (Adapted, Wood 1972)

are directly controlled by several ecological factors viz. SOM content, rainfall and temperature variation trends, inherent soil fertility, and mechanical manipulation of soil, i.e. tillage intensity.

For recommending textural specific N recommendations, the following points should be considered (Meyer 2013).

1. Ascertain the moisture regime, cane stage, and intervening period managements.
2. Verify the achievable land productivity with desired quality parameters.
3. Organic carbon and clay content.
4. Delineate the main soil properties such as soil color and structure
5. Estimate the soil N mineralization potential
6. Inherent nutrient fertility of the soil
7. Ratoon cane stage generally has higher N recommendations because of already developed root biomass. Soil mineralization potentials and target yields are the primary input to be used for calculating the N-requirements of the sugarcane. Here integrated nutrient management (INM), i.e. use of inorganic fertilizers along with organic inputs to harvest the full benefits of both the sources. On an average, additional one t ha^{-1} yields require about 1 kg of N, mainly when already yield potential of 100 t ha^{-1} achieved (Vuyyuru et al. 2019).

18.6.2 Phosphorus

Phosphorus is the second most important nutrient required by the plants after N for completing their life cycle and carrying out different metabolic activities such as photosynthesis, root development, tillering, etc. Despite it, P has a role to play in CO_2 assimilation from photosynthesis. Mostly, P absorbed by the roots from the soil solution and its form is pH-dependent. In the acidic range viz. <7.0 P absorbed as $H_2PO_4^-$ (dihydrogen phosphate), while in higher range viz. pH >7.0, HPO_4^{2-} (monohydrogen phosphate) used. However, P is not mobile in soils and are generally not available to new plant canes; therefore, utmost care is to taken while deciding P-fertilization as a higher dose has environmental implications. In Punjab, P recommendation is made only based on the soil testing reports; the soils having <12.5 kg ha^{-1} are recommended with 30 kg P_2O_5 ha^{-1} (PAU 2018-2019). Generally, cane crop could use up a small amount of P compared to other crops near to about 20 kg ha^{-1}. On deficient soils, P application significantly improves both productivity and quality (Fageria and Baligar 2001). Midlands Experiment reported by Meyer and Dicks (1979) delineates that P application despite increasing yields has a non-significant impact on saccharose % age of canes (Tilib et al. 2004). In tropical and subtropical regions, P deficiency is higher on the red oxisol soils due to fixation of the applied P. Therefore, judicious use of P fertilizer is a must as higher doses sometimes instead of increasing decreases the sucrose per cent cane, especially in later ratoons receiving top dressing (Du Toit 1962). Notably, throughout the globe, cane farmers applied higher doses of P fertilizers, thereby forming pockets of high P, which is itself a challenge as this higher P status has ecological consequences in terms of water and soil pollution and thereby affecting the plant, animals, and finally human health. Thereby its judicious and need-based application in sugarcane crops is a must.

18.6.2.1 Phosphorus Cycle in Soils

In soils, in comparison to other nutrients, P has a slow and complex cycle affecting life in one or another way. Solubilization and fixation of mineral phosphates through microorganisms and precipitation by soluble forms of Al, Fe, or Ca and adsorption by sesquioxides clay colloids, respectively, constitute the critical parts of the cycle of P in the soils, which further decides its availability to the plants through roots from the rhizosphere (Fig. 18.9) (Meyer 2013). Further, soluble P and fixed/unavailable P are found at the surface in biogeochemical reactions and deep in geochemical reactions, respectively. In virgin soils, generally, P held in organic or inorganic forms and is unavailable for the plant use while older sugarcane fields offer higher P accumulation in the soil. Therefore, in already cultivated soils, P status is very high as it got fixed, therefore also in paddy season, its application is omitted to reduce the cost of cultivation, while it is recommended in the wheat (*Triticum aestivum*) during sowing on soil test basis.

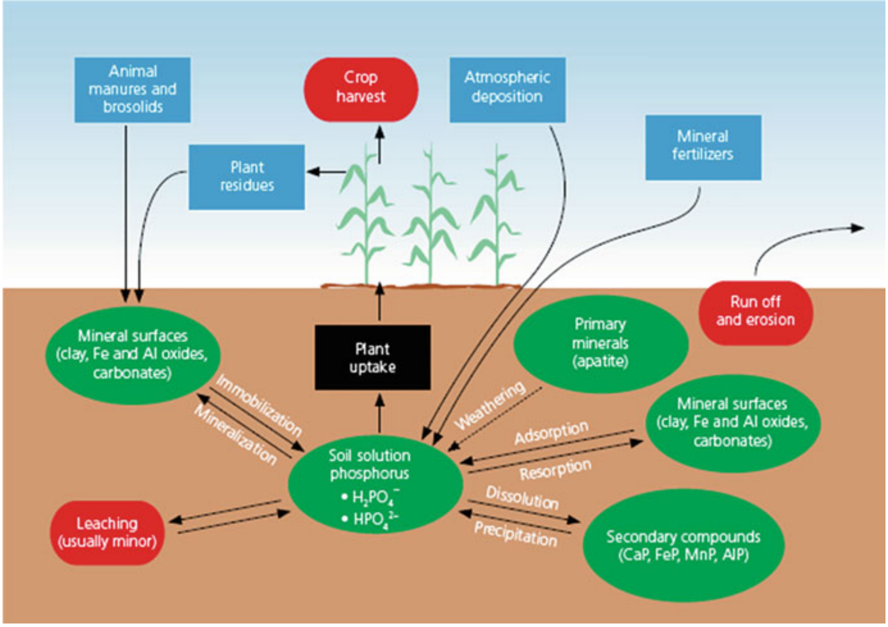


Fig. 18.9 The soil phosphorus cycle (Adapted, Meyer 2013)

18.6.2.2 Factors Affecting Phosphorus Availability

1. Among different mineral P forms, water-soluble forms $H_2PO_4^-$ and HPO_4^{2-} anions from $Ca(H_2PO_4)_2.H_2O$ (mono-calcium phosphate) are readily available to plants while some forms viz., $AlPO_4$ (aluminum phosphate) and $Ca_3(PO_4)^{2-}$ (tricalcium phosphate) and $FePO_4$ (Ferric phosphate) are slowly and very slowly available (Heck 1934). However, from $AlPO_4$, sugarcane also fulfils their P requirements to a significant extent (du Toit 1957) depending upon the soil pH levels, which is also delineated by the observed temporal changes in phosphate of Al, Fe, and Ca.
2. *Fixation by hydrous oxides*: Fixation by the hydrous oxides decreases the availability of P in the soil solution and hence supply to the plants for meeting their requirements. Many indicators in the sugar industry are referred to delineate this fixation and to recommend different doses of P fertilizers, as per the fixation observed to strengthen the soil solution from outside viz. phosphate desorption index (PDI) (for South Africa) (Meyer and Dicks 1979) and phosphorus buffer index (PBI) (for Australia) (Burkitt et al. 2000).
3. *Soil pH*: At pH between 5.5 are 7.2, P availability is higher to cane, when $H_2PO_4^-$ and HPO_4^{2-} will be concurrently available. Under the alkaline soils with pH >9.3, the dominance of PO^{-4} ions observed which further precipitate as Ca or Mg salts while under acidic soils (pH <5.0), P becomes unavailable. Some other nutrients viz. Al also got fixed but not to the extent of P-fixation. Reclamation of these soils by application of gypsum to alkaline soils and lime to acidic soils will

improve P availability in soils and to the plant roots (Meyer and Wood 1989), which further improves the overall yield potentials of the sugarcane crop whether it is the seed or ratoon crop.

18.6.3 Potassium

For sugarcane growth and photosynthesis, K is an essential and critical player for maintaining the plant's moisture content, distribution of nutrients throughout the plant, and improving the NUE. Potassium is the most abundant essential elements for the formation of cane juice. The K is predominantly present in inorganic minerals such as feldspars and micas. Sometimes, total K seems to be high, but due to lesser solubility of the K salts in these minerals, its deficiency symptoms appeared (Brar et al. 2008; Bhatt and Sharma 2013). Typically, roots extract the K ions from the soil solution for meeting its requirements. When K absorbed, showing its deficiency in soil solution which replenished by the mineral lattice viz. Illite. Soil solution must be strengthened by K fertilization, otherwise, at upon one time, minerals may not be able to maintain the soil solution strength, and then sugarcane will soon show typical symptoms of K deficiency. Therefore, K deficiency in the soils must be timely delineated, and deficient soils must be supplied with proper K fertilizers. Therefore, plants will not suffer from its deficiency and there will be not any loss in the productivity of the cane, which further helps to improve the livelihoods of the cane farmers.

18.6.3.1 Potassium in Soil Solution

Under normal conditions, K presents least in organic while mostly in inorganic form and its range in soils and lithosphere generally present in as 0.8 and 2.6%, respectively (Lindsay 1979). In soils, K is present in soluble K (0.1–0.2% of the total), exchangeable K (1–2%), non-exchangeable K (1–10%), and mineral K (90–98%) forms (McLaren and Cameron 1996), out of which soluble and exchangeable forms generally available to the plants through the soil solution while non-exchangeable and mineral forms are slowly available and unavailable, respectively.

Feldspars and micas on weathering release only small amounts of K into the non-exchangeable pool, which further consists of 2:1 lattice clay, from where K released into the soil solution to replenish it, which further improves its intake into the plant roots (Brar et al. 2008). Around one-tenth of the total available K is present in the soil solution (Fig. 18.10). Potassium also being released from the non-exchangeable form to exchangeable one, particularly in alluvial soils and those derived from granite/schist (Brar et al. 2008). Non-exchangeable forms should be considered while finalizing the potash fertilization in sugarcane. Potassium fertilization improves the overall yield and juice quality, decreases insect-pest attacks, improves the NUE, and helps in better root growth.

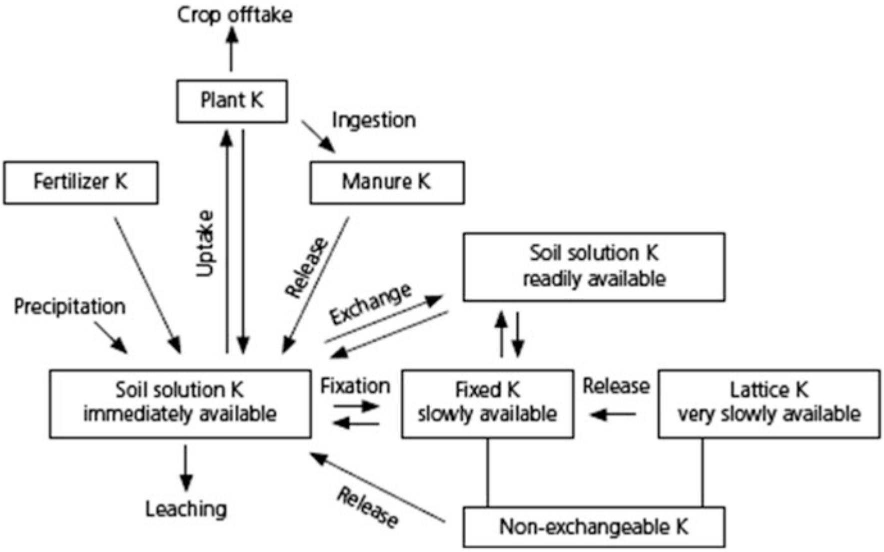


Fig. 18.10 Potassium in the soils (Adapted Syers 1998)

18.6.3.2 Factors Affecting Potassium Availability in Soil

Initially, K utilization during sugarcane growth, not a static but is a dynamic process. Generally, in India particularly in Punjab, K is given not much attention due to inherent capacity of soils to meet the K requirements and dominance of Illite minerals responsible for it (Brar et al. 2008). But, with time at several locations, these minerals are not able to saturate the soil solution, from where the plants absorb the required amounts and then typical K deficiency symptoms appeared. Therefore, at those sites/areas, potassic fertilizers must be added to maintain K saturation levels in soil solution for proper supply of K nutrients to the plants so that land productivity should be maintained level.

Clay Mineralogy and Potassium Fixation in Punjab Soils

Among the various depleted nutrients, K is of prime concern as exhausted at 300 kg ha^{-1} year^{-1} in the State, which traditionally not returned back into the soils by Punjab farmers. The soils of Punjab are generally assumed to have an abundance of K containing minerals viz. illite, smectite, but now things had changed. On average, crops deplete 581,560,000 kg K year^{-1} from soils of Punjab, while 9,929,000 kg K year^{-1} additions, which is equivalent to 1.7% of the loss. Alone rice-wheat sequence removed 300 kg ha^{-1} year^{-1} of potash from 6 inches of the rhizosphere, and it was reported that the rate of potash removal from soils of Punjab increased from 136 kg ha^{-1} (1970–1984) to 149 kg ha^{-1} (1984–2004) (Brar et al. 2008). The K in soils of these regions has completely exhausted in the last 125 years if undressed (total K reserves 40,000 kg ha^{-1} and K loss 300 kg ha^{-1} year^{-1}). In N/K fertilizer trials, K applications either failed to increase the leaf K content (Wood and Meyer 1986) might be because some soils exhibit strong K fixing properties. Additional doses of K will increase the quantity available for the plants. After multiple K fertilization, the equilibrium state reached where minimum K got fixed while a higher fraction of potash available for the plant uptake. Potassium fixation-release mechanism still needs more attention though generally, 1:1 lattice clays (Kaolinite) fixed little potash compared to 2:1 lattice clay (montmorillonite and smectite). Therefore, understanding the clay mineralogy of a location is too crucial before finalizing the K doses to be applied. Ferralsols (high weathered soils) that contain mainly Kaolinite fix little potash when compared with verily in cool, wet conditions, thereby supplying higher fractions of K to the plant roots through soil solution (Brar et al. 2008).

However, upon each harvest, K depleted from the soils led to the rapid opening of cleavage points of minerals, loss of active cation holding sites, leaching of silicic acid, and narrowing down of $Si:O_2$ ratio. Excessive K loss results in acidic conditions, which further alter all the soil water nutrient interphase. Fields with low sugarcane productivity usually received high N and critically low K levels. Low K levels result in lower N-use efficiency, which further results in high reducing sugars and low sucrose. Further, illite altered to vermiculite, if the excessive withdrawal of K is not checked or potash is not applied through fertilizers, then many features of natural soil viz. good tilth, non-tearing of roots under water stress, Mg^{2+} retention may be lost forever. Therefore, the strategy must be planned in sugarcane to add need-based K at least what is removed from the soil, to maintain the potash reserves; otherwise, it might be too late if K deficiency symptoms waited for potash application in sugarcane. Sugarcane—a heavy feeder of nutrients as only aerial parts of sugarcane in one hectare generally has more than 200 kg of K, which, if is in short supply, then affected quality parameter and cane productivity. Potassium is a must for the synthesis and movement of sucrose from leaves to other parts, therefore decreases the attack of insect pests. Potassium also controls the opening of stomata, therefore plant supplied with required K, withstands better in water-stressed conditions than the K deficient plant. Finally, K translocates sucrose from leaves, controls opening of stomata, improves NUE and therefore, it is now imperative to go for balanced fertilization in letter and spirit (Bhatt et al. 2019).

Soil Texture

Higher the clay fractions, more excellent the K fixation while lesser the clay higher will be the leaching losses. Heavy textured soils fixed fraction of K than leaching as compared to that in the sandy soils (Arenosols and Regosols), because of lesser attractive forces, which further results in higher leaching losses of K, thus results in lower K use efficiency. Hence, higher K doses with higher splits recommended for improving K efficiency.

Soil Temperature and Moisture

Soil temperature and moisture are the two most important factors that might influence the K uptake and hence the availability of applied potash. Further, their interaction also affected the availability of K (Leverington et al. 1962). Low soil temperatures in the winter under wet conditions supplied lesser amounts of potash to sugarcane (Donaldson et al. 1990) even in well-supplied K soils; therefore, K fertilizer should be applied soon after harvest. Therefore, soil temperature and moisture must be considered before finalizing the K doses.

Antagonism Effect of Calcium and Magnesium

Higher levels of soil Ca and Mg may inhibit the availability of potash throughout the globe under varied textured soils (Wood and Meyer 1986; Santo et al. 2000). Higher levels of Ca hinder diffusion across soil solution and roots, responsible for K movements and Mg, especially when base saturation of (Ca+Mg)/K more than 20 (Donaldson et al. 1990). Agricultural field irrigated with irrigation water having a high Mg level showing the K deficiency symptoms (Santo et al. 2000). Therefore, Ca and Mg prove to have an antagonism effect on the K availability to the plants, and therefore, before finalizing the K dosage for the sugarcane, the inherent Ca and Mg levels must be considered.

Sub-soil Potassium

Soil sampling for cane fertilization is restricted to the topsoil (0–15 cm—centimeter), while canes could remove nutrients from greater depths; therefore, inherent soil fertility must be considered well before finalizing K dosage to sugarcane. Generally, sub-soil could fulfil half of the K requirements of the cane crops (Grimme 1980), mostly which is not considered during sampling. Therefore, the sub-soil inherent capacity to supply available potash to sugarcane is an essential factor and must be explored before finalizing K dosage to the canes for improving both cane land productivity as well as quality.

Response Plant/Ratoon

Different crops viz. plant or ratoon canes respond differently to applied potash. Ratoon cane responded better to applied potash as potash reserve of the soils changed to available forms during the intervening fallow period. Hence, the crop cycle needs considerable attention. In Uttar Pradesh, plant canes did not respond to applied K fertilization as compared to the ratoons in mollisol (Sachan et al. 1993). However, in Brazil, not the plant neither the first ratoon rather second and third ratoon responded to applied K fertilization (Paneque et al. 1992). First ratoon responses to K fertilization affected by K rates in plant cane. These interactions unavoidably enhance the challenges of delineating cane response to applied K fertilization.

Inherent Potash Status

Generally, soils inherent supply is considered sufficient for meeting the cane K requirements, but with time K deficiency and hence, K deficiency particular symptoms appeared; therefore, its top dressing becomes important (Brar et al. 2008; Bhatt and Sharma 2013). Relationship between applied K and exchangeable K in soil solution well expressed in Fig. 18.11.

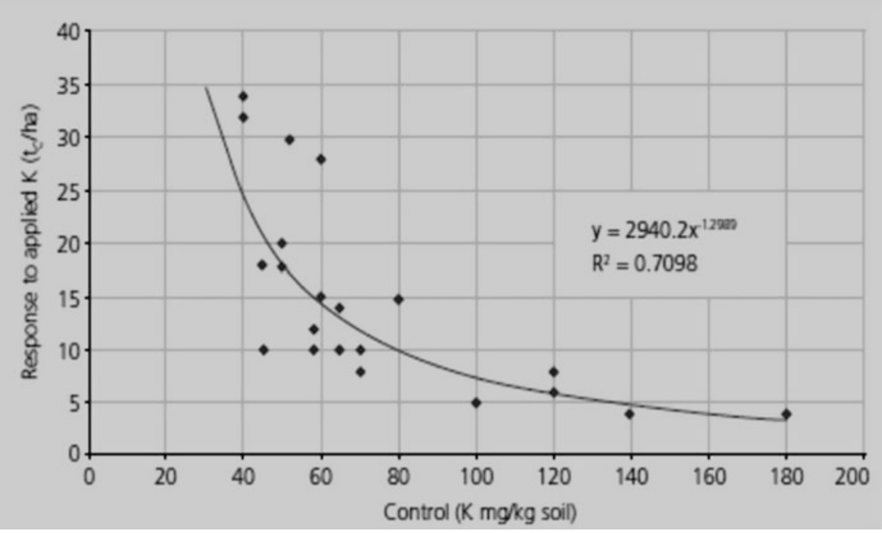


Fig. 18.11 Association between applied K and exchangeable K levels in soils (Kozak et al. 2005)

Increased pole percentage and reduction in fiber content is responsible for improved sucrose recovery and yields when K applied to deficient soils as it reduces the starch content of canes (Wood 1962). It is established that potash at 0, 92, and 184 kg K ha^{-1} will not improve the quality parameters of sugarcane significantly (Donaldson et al. 1990).

Ghaffar et al. 2013 during their experiments during 2006 and 2007 reported maximum yield (116 and 107 t ha^{-1}) with the application of 168 kg K_2O ha^{-1} in two splits, while the highest Brix (20.4 and 20.8%) sucrose (17.5 and 18.2%)) and commercial cane sugar (12.95 and 13.60%) were obtained with the application of 224 kg K_2O ha^{-1} in two splits. Generally, low K viz. <137.5 kg K ha^{-1}, responded to applied potash as then the soil solution is hungry and must be replenished. Even then, this fixed 137.5 kg K ha^{-1} range is under doubt that two differently textured soils with let us say 130 and 85 kg K ha^{-1} being held the same recommendation or not, so a long way is to be travelled for dealing this issue more accurately. To date, for both soils, we have the same recommendations for the farmers. On the other side, if higher doses of potash used, then it will harm the quality as K holds saccharose in solution by forming complexes (Clarke 1981), because hiked K levels in juice, increased sucrose solubility which further means that crystal yield will be lower (Irvine 1979). Luxurious K consumption positively encourages cane lodging, ash in raw sugar, and produces juice of lower quality (Stevenson et al. 1970; Kingston 1982).

In South-Asia, Indo-Gangetic plains (IGPs) supposed to supply potash due to its mineralogical make-up, however, due to cultivation of high yielding cultivars and skipping potash fertilizers; its deficiency started in some pockets, which needs to be identified as K deficiency has a pessimistic effect on metabolic activities of sugarcane and for maximum economic cane yield. As 200 kg K_2O ha^{-1} fertilized sugarcane plots yielded 31.2% higher land productivity as compared to the control plots (Khosa 2002) with 2.0% higher sucrose content.

Irrigated Conditions

Irrigated sugarcane removes higher contents of potash as compared to the rainfed conditions. On an average, yearly canes (under rainfed conditions) contained 214 kg K ha^{-1}, whereas similar cultivars could remove up to 790 kg K ha^{-1} under irrigation conditions in South African conditions (Wood 1990). Therefore, balanced fertilization is a must, applied potash had a role in improving the quality as well as quantity parameters of sugarcane as depicted in Table 18.5 (Chatterjee et al. 1998).

Under water-stress conditions, K significantly increased stomatal diffusive resistance, resulting in lower transpiration rates and increased leaf water potential, cane length, sucrose content in juice and cane yield (Filho 1985; Sudama et al. 1998; Ghaffar et al. 2013) by controlling the stomatal guard cells (Filho 1985; Malavolta 1994). Some workers reported no significant changes in yield parameters on applying potash (Lakholive et al. 1979; Olalla et al. 1986; Ghaffar et al. 2013), while some reported a significant increase in cane quality as well quantity (Korndorfer 1989; Prasad et al. 1996; Nagarajah 2006). Further, sufficient K from the non-exchangeable K reserves could be acquired by sugarcanes in the upper layers of the soil and sub-soil under certain conditions, more particularly when the buffering capacity of the soil is high (Rabindra et al. 1993).

18.6.3.3 Effect of Potassium on Sugarcane Quality

Improving cane quality is the only way to strengthen the sugar industry. Grinding cane with a high percentage of recoverable sucrose is much more profitable as this will reduce the cost per unit ton of produced sugar. The quality of juice is vital in this regard as it determines the maximum yield of sucrose. Unfortunately, however, the content of sucrose in the cane is primarily affected by variety, and climatic conditions and the fertilizers applied only to a relatively small extent. Potassium can increase the Brix of the cane juice without much increasing the cane yields (Dang and Verma 1996). Most of K fertilizer tests showed an increase in cane sucrose did not accompany the cane yield response to K (Table 18.6). Wood et al.

Table 18.5 Effect of K manuring on height, stalk population and yields of sugarcane (Adapted, Donaldson et al. 1990)

K (kg ha^{-1})	Cane (t ha^{-1})	Pol % cane[a]	Sugar (t ha^{-1})	Stalk height (cm)	Stalk population ($\times 10^3$)
0	88	13.2	11.6	240	86
300	112	13.5	15.1	273	93
600	114	13.3	15.1	278	88
LSD = (p = 0.05)	17	0.9	2.5	17	14

[a] Amount of sucrose in cane

Table 18.6 Response of sugarcane found from 1990 to 1993 at a site in Mauritius with only 0.16 cmol exchangeable K kg^{-1}

	Cane (t ha^{-1})			Sugar (t ha^{-1})			IRSC[a]	
K (kg ha^{-1})	Plant crop	First ratoon	Second ratoon	Plant crop	First ratoon	Second ratoon	First ratoon	Second ratoon
0	106.6	94.6	77.2	11.59	10.69	9.25	11.3	11.3
60	98.7	103.3	93.6	11.01	11.98	11.32	11.6	11.3
120	103.9	108.9	92.3	11.46	12.63	11.57	11.6	11.2
180	110.1	108.2	91.1	11.86	12.94	10.77	11.5	11.0
LSD ($P = 0.05$)	13.3	10.1	10.3	1.77	1.54	1.54	0.7	0.9

[a] Industrial recoverable sucrose % cane

(1990) observed that, in the absence of a cane yield response, the rate of K had little impact on cane quality in South Africa. However, contradictorily Gulati et al. (1998) observed maximum cane yield and number of millable canes in two equal splits (50% at sowing and 50% at monsoon end) with K fertilization without having significant effects on the juice quality. Most importantly, it was found that excessive soil uptake of K depresses the recovery of saccharose during milling. According to Filho (1985), K tends to increase the solubility of sucrose during sugar processing, thus maintaining a certain amount of saccharose in solution, one K^+ tying up a molecule of saccharose

Wood et al. (1990) delineated a significant depression in cane saccharose concentration after an application of 183 kg K ha^{-1}. In long-term trials in Australia, Chapman (1980) observed that 196 kg K_2O ha^{-1} slightly declined cane sucrose concentration compared to no K treatment. Korndorfer (1989), who observed that vinasse (distillery slopes) increased cane yield from 98 to 127 t ha^{-1} when applied at 120 m^3 ha^{-1} to a dark red dystrophic latosol in Brazil. He also observed the decreased recoverable cane concentration from 15.0 to 13.1%. Potassium, despite its role in sugarcane plants, must be kept sufficient in the soil solution to produce optimum yields with desired cane juice quality.

18.6.4 Micronutrients

Being required in small amounts, some nutrients viz. Zn, Cu, Fe, Mn, B, Cl, Mo, Co, and Nickle, which are equally instead sometimes more important from macronutrients are termed as “Micronutrients.” Their role could be better delineated through Fig. 18.12.

In sugarcane crop, these are essential ones and required in minimal amounts. It appears that micronutrients, in general, produce non-significant increases or decreases in the Brix. There were significant yield responses to Zn application, but none of those examined showed any significant effects on sucrose content (Madhuri et al. 2013). However, in the case of Fe, there was a significant increase in the

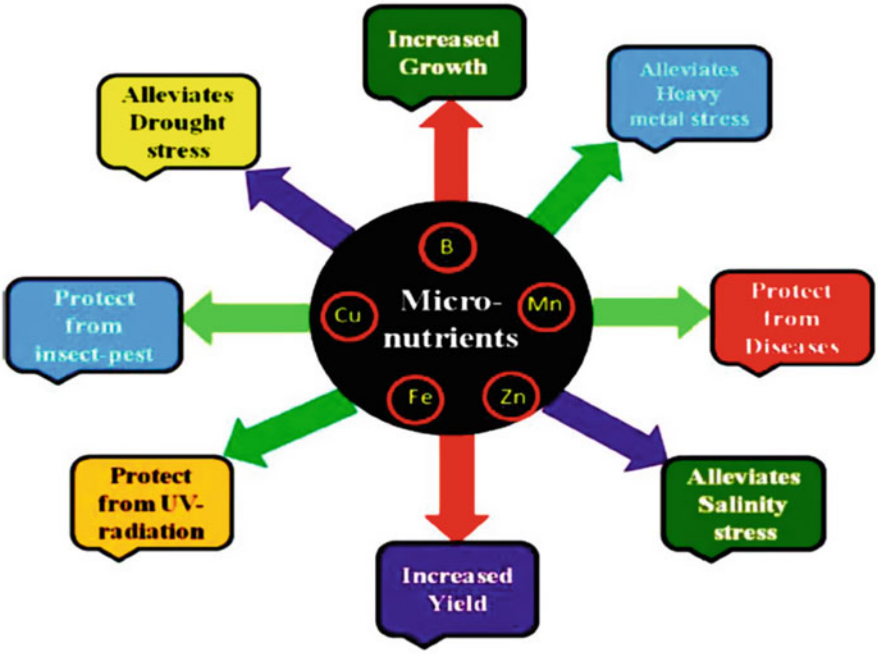


Fig. 18.12 The response of micronutrients in biotic and abiotic stresses (Adapted, Tripathi et al. 2015)

percentage of sucrose cane where chlorotic cane was sprayed with ferrous sulfate (Madhuri et al. 2013). The mission for the most suitable fertilizer and the most balanced fertilization for maximum sugarcane productivity is the current requirement. Sustainable sugarcane fertilization triggers the plant physiological processes in the most effective ones, which further improves the yields and overall quality. Micronutrients perform vital functions as enzyme activators in sugarcane (Malavolta 1974; Epstein 1975).

Generally, sugarcane crops not responded to micronutrients in terms of cane yields (Alvarez and Wutke 1963; Siqueira et al. 1979; Azeredo and Bolsanello 1981; Madhru et al. 2013), while in some experiments, Cu and Zn application have significant effects (Alvarez and Wutke 1963; Cambria et al. 1989). Thereby, identifying their critical limits is somewhat more critical which may be varied in texturally different soils range below which responsible for the definite symptoms, which needs to be corrected otherwise affect the cane/grain yields (Marinho and Albuquerque 1978). As far as B is concerned, Alvarez and Wutke (1963) observed B response more particularly in the deficient soils up to the first ratoon crop. “Hidden hunger” (plant suffers but shown no symptoms) generally shown by the sugarcane crop about micronutrients (Orlando Filho et al. 2001). Micronutrient availability and absorption affected by several factors viz. soil type, cane cultivars (early or mid-late group), and seasons weather winters or summers (Madhuri et al. 2013).

The Fe > Mn > Zn > Cu > B > Mo is the pattern with which they exported to sugarcane as its application in furrows did not shows any response. Thereby, it is recommended to test soils before sugarcane micronutrient fertilization to address the hidden hunger for overall improving the cane yields as well as quality (Orlando Filho et al. 2001). Boron is involved in the cell division, cell maturation, cell wall lignification, and inhibition of starch formation considered necessary (Sobral and Weber 1983). Similarly, Cu being acted as an activator of several enzymes (fenolase, laccase, polifenoxolidase) and controlled the photosynthesis process (Taiz et al. 2004).

Manganese involved in the proliferation of cell, photosynthesis, and enzyme activation (Sobral and Weber 1983). Molybdenum controlling sugarcane biological N fixation and nitrate assimilation by affecting the nitrate reductase enzyme (Sobral and Weber 1983; Orlando Filho et al. 2001), while Zn being essential for tryptophan synthesis which further vital as it controlled different growth enzymes and pre-cursor of indole acetic acid (IAA) (Orlando Filho et al. 2001; Taiz et al. 2004). As per Gomes-Alvarez (1974), age of canes, ambient temperature, rainfall patterns, day time viz. morning, noon, afternoon, cane cultivars, and inherent soil fertility affecting cane leaf nutrient concentration. Therefore, nutrient concentrations in cane leaves affected by several factors which need to consider while finalizing the fertilizer schedule of sugarcane.

The yield of canes affected by the micronutrient status of the soils as deficient soils certainly had lower yields as theses micronutrients are very significant and hence must be biofortified, which is more effective than soil applications. During the 1960s, Alvarez and Wutke (1963) while evaluating micronutrient effects on the sugarcane for isolated applications B, Mo, Fe, and Cu delineated a positive relation between micronutrients yields and sugarcane yields. In light-textured soils, Alvarez and Wutke (1963) reported that Cu and Zn chelates promoted sugarcane yields and juice quality. Azeredo and Bolsanello (1981) reported a 30% hike in productivity when micronutrients solution at 5 g l^{-1} sprayed. Franco et al. (2011) found that the use of 2 and 4 kg ha^{-1} of B in sugarcanes promoted girth of canes and improves the cane juice Brix in seed crops without having encouraging results, particularly in seed canes as far as Zn application was concerned. Mellis et al. (2008) evaluated the response of plant cane for Cu, Zn, Mn, and Mo in sugarcane producing regions observed 18% yield increase. Hence, the micronutrient application in the sugarcane played an important role (Mellis et al. 2010).

Micronutrients viz., Cu, Mn, and Zn chelate on spraying (at doses of 1.0 and 1.5 l ha^{-1}) increased stem productivity by 10 and 15%, respectively. Micronutrient sources applied to stems did not lead to significant increases in recoverable sugars (Fernanda et al. 2017). Further in Punjab, generally Fe deficiency in sugarcane, reported on light-textured and calcareous soils in the younger leaves, under which yellow strips appeared in the green leaves. Under severe deficiency, leaves become white and plant stunting. For correcting Fe deficiency well on time, 1% spray of ferrous sulfate recommended for 2–3 times at weekly intervals as and when symptoms appeared (PAU 2018-2019).

18.7 Fertigation

Fertigation involved the application of dissolved fertilizers through modern irrigation systems to the sugarcane crop. This system becoming popularized between the farmers as reduced labor, enhanced nutrients and water use efficiency, higher land productivity and quality, reduction in irrigation time, and environmental protection are some of the benefits of this method (Haynes 1985; Bachchhav 1995).

18.7.1 Fertigation and Sugarcane Yields

Different researchers revealed different conclusions as far sugarcane fertigation is concerned on nutrient and water use efficiency as some delineated no significant improvement in cane yields (Parikh et al. 1996; Selvaraj et al. 1997) while some recorded significant improvement in cane yields along with fertilizers saving (Shinde et al. 1998). Some locations reported significantly better results at 50% recommended dose of fertilizers (RDF) than 100% RDF with flood irrigation (Anon 1997). Drip irrigation (at 40% of surface irrigation with 175 kg N ha^{-1}) recorded higher cane yield over conventional furrow irrigation (Selvaraj et al. 1997; Shinde et al. 1999). Liquid fertilizers through drip also promoted cane yields significantly (20.8%) (Shinde et al. 1999). Patil et al. (2001) observed 25%fertilizer saving along with a 20.74% yield increment in drip irrigation. Vaishnava et al. (2002) obtained higher cane production with fertigation of 80% RDF, thereby saved 20% of fertilizers. Mahendran and Dhanalakhmi (2003) expressed through their experiments proper cane yield parameters (plant height, tiller production, leaf area index, and dry matter production) and yield attributes (millable canes, cane length, cane girth, cane and sugar yields). Batta et al. (2005) reported leaching losses and mineralization of ammonical N into nitrates' main reasons for lower N-use efficiency, which could be enhanced by adopting drip irrigation. Further, water-soluble fertilizers had a greater influence on quality parameters when flood irrigation shifted to drip one (Bangar and Chaudhary 2004). Mahendran et al. (2005) reported higher Brix (19.40), pol (17.26), and purity (89.00) percentages under drip irrigation compared to flood irrigation. Therefore, as far as irrigation is concerned for sugarcane farming, the primary emphasis should be put on the fertigation as it overall improves the cane yields and quality by improving the nutrient use efficiency and reducing leaching losses.

18.7.2 Fertigation and Water Use Efficiency

Fertigation enhanced water use efficiency by 2.7% by reducing the leaching, drainage, seepage, and evaporation losses up to 50–55% (Hapase et al. 1992, 1993; More et al. 1995). Drip irrigation resulted in higher water use efficiency (1.147 t ha^{-1} cm^{-1}) (Deshmukh et al. 1996). This improvement in the water use efficiency is site and situation-specific as in Patna; it became double than the conventional irrigation systems (Anon 1997). Sugarcane productivity was significantly higher with drip irrigation (Selvaraj et al. 1997) as 840 kg cane ha^{-1} cm^{-1} of water, reported under drip irrigation. Further, reported higher water use efficiency with drip irrigation varied from 42 to 52% (Raskar and Bhoi (2001) to 30.6% (Mahadkar et al. (2005) compared to flood irrigation. Therefore, more particularly for the water-stressed regions viz. central Punjab, India, the government must subsidize the drip irrigation with more incentives to popularize the drip irrigation in between the cane farmers.

18.7.3 Fertigation and Nutrient Use Efficiency

Being a higher nutrient consumptive crop, higher doses of fertilizers are applied to sugarcane crop which might responsible for higher leaching losses. Further, there is a need to improve NUE. Fertigation (applying nutrients along with irrigation water through drips) proved a critical technology in this regard than solid broadcasting applications (Prasad et al. 1983). Though water as well nutrient use efficiency improved to a significant extent even though this not delineated in the overall cane yields (Ng Kee Kwong and Deville 1994). Under drip irrigation, highest nutrient use efficiency reported even at a half dose of RDF. However, Bangar and Chaudhary (2004) explained significant improvement in cane yields along with improved nutrient use efficiency under drip irrigation. Further, N and K contents in the index leaf of sugarcane were reported higher in drip method at 1.0 and 0.8 IW/CPE (irrigation water to cumulative pan evaporation) ratio, whereas the P content in the index leaf was highest in drip at 1.0 IW/CPE ratio which was because of the reported higher nutrient use efficiency (Goel et al. 2005).

18.8 Land Management Practices for Improved Sugarcane Yields

Declining SOC, arising micronutrient deficiencies, and an increase in soil acidity are some of the outcomes if sugarcane cultivation is done on the same piece of land for a longer duration. Further, achieved “Yield Plateau” stressed us to rethink the way we managed soils as yields become stagnant now, which further resulted in the sugarcane yield and sucrose decline. Therefore, scientists/researchers need to rethink the judicious management of the soil and to advocate mulching of paddy straw/sugarcane trash, green manuring, minimum tillage, use of organic amendments viz., press mud, FYM to the cane farmers (Van Antwerpen et al. 2003; PAU 2018-2019) as there is a need to maintain the soil humus. Further, azotobacter has a role in improving nutrient availability. Throughout the globe, now focus/research strategies generally planned at the following land management practices.

18.8.1 Minimum Tillage

Intensive tilling of the soil breaks down the soil aggregates, and thereby, the organic matter becomes available for soil microorganisms for their feeding through which releasing CO_2 into the atmosphere, which further causes global warming (Kumar et al. 2017). Further, zero tillage reported increasing the bulk density of soil after 3–4 years (Bhatt et al. 2016). Thereby, minimum tillage is always advocated for sequestrating the carbon into the soils for mitigating the global warming consequences on cane farming (Kakraliya et al. 2018). Further, profound ploughing benefits were of short-duration and not even justify its expenditure of tilling the soil. Minimum tillage improved SOC, decreased soil bulk density (Bhatt 2016) and overall, improved soil physical, chemical, and biological properties of the soils in its way and ultimately there are net benefits of the minimum tillage as compared to the conventional intensive tillage (Bhatt 2016; Bhatt and Arora 2019; Meena et al. 2019a; Rani et al. 2019). Minimum tillage proves to build up carbon in the soil; however, it required a set period to have its significant effects (Bhatt 2016). Under minimum/zero tillage, decreased CO_2 emissions by higher carbon sequestration and increased methane (CH_4) uptake offset by higher production of nitrous oxide (N_2O), a greenhouse gas with higher potential (Chatskikh and Olsen 2007). The warming potential means the radiative forcing impacts of each greenhouse gas relative to CO_2, as detailed in IPCC (2001). Under minimum tillage, denitrification losses are higher due to formation of microaggregates (<250 μm) within macroaggregates (>250 μm) that resulted finally in the creation of dense structure (Regina and Alakukku 2010), microsites which are an-aerobic (Hermle et al. 2008) and higher oxygen competition (West and Marland 2002). Therefore, neither intensive nor zero but minimum tillage might be a suitable answer.

18.8.2 Soil Crusting

Soil crust creates a hindrance for the free movement of water, air, and finally, roots, and this resulted in lower yields of poor quality. The hard crust is being formed at a depth of 0.5 feet in the soil by raindrop impacts, which disintegrate of the soil aggregate into individual soil particles. Now first sand then silts and finally clay particles filled the pores as per Stroke’s law and form the plough hardpan, which further led to soil compaction under conditions when soil solution has too low electrolyte concentration. Soil crusting assumed to be pre-cursor for the soil erosion as it resulted in runoff flows because of lesser allowed infiltration. Research findings suggest that mulching on the whole surface will reduce the crust formation and erosion damage in terms of soil and water loss (Bhatt and Khera 2006). In sugarcane, to break formed crust, cross sub-soiling at 1.0 meter (m) spacing recommended after 3–4 years with the help of sub-soiler up to the depth of 0.5 m, followed by planking to break clods, hardpan and to improve water and air intakes and which finally improves the sugarcane production (PAU 2018-2019).

18.8.3 Integrated Nutrient Management

Integrated nutrient management viz. judicious application of chemical fertilizers (urea, diammonium phosphate—DAP) and organic amendments (FYM, if prepared in pits), played a very crucial role in improving soil health, and finally quantity and quality of the produced sugarcane. In Punjab, 20 t ha^{-1} of FYM recommended 15 days before planting will serve the purpose (PAU 2018-2019); however, by applying this, the N recommendation gets reduced from 150 kg N ha^{-1} to 100 kg N ha^{-1}, which on the one side reduces the cost of cultivation while on the other, improved, different properties of soil. Further, Azotobacter/Consortium biofertilizer, when applied at 10 kg ha^{-1}, would help in improving both cane yields and sucrose content (PAU 2018-2019). Therefore, the INM must be encouraged between the farmers.

18.8.4 Green Manuring

Green manuring helps to improve the soil health by improving the SOM and hence, yield potential of planted as well as ratoon sugarcane crop (Nixon 1992; Nixon and Simmonds 2004; Meena et al. 2018, 2020). Increased SOM helps in improving the different soil physical viz. topsoil air-filled porosity and steady-state ponded infiltration rates, chemical viz. pH, EC, and biological properties and finally improved sugarcane yields.

18.8.5 Soil Conservation

For sugarcane farming at sloppy hill lands, which are prone to soil erosion, need to adopt the suitable soil conservation practices (Platford 1979) (to keep the farm water in farm and not allowing it to become runoff) must be identified and recommended to the hill farmers of the state. Under soil erosion, gully erosion is the main with a complex gully network. The government already spends crores of rupees for controlling soil erosion by installing check dams in the higher orders but with time they are either broken down by local farmers (who used to enter with their animals through higher-ordered gully for grazing) or silted up and thus become non-functional. It is established that lower ordered gullies are the main culprits for collecting runoff water from each nook and corner of the catchment to the higher-ordered gullies. Therefore, lower ordered must be handled on a priority basis (Bhatt and Kukal 2016). The main aim is to reduce erosivity of raindrops as well as erodibility of the soil so that sugarcane farming will not be affected at sloppy areas.

18.8.6 Trash Management

Sugarcane trash instead of burning if applied on the soil surface acted as mulch thus shared the following benefits:

1. Direct hot sunlight rays are not able to hit the bare soil, thereby reducing the energy (required to cause phase change from liquid to gas) and finally lowered the maximum soil temperature during noon hours.
2. Decreased the vapor pressure gradient, thereby hinders the free exit of vapor.
3. Reduces the wind speed close to the soil surface and thereby reducing air's vapor lifting capacity.
4. Improved carbon sequestration of when fertilizers placed below the straw loads, instead of applying over the trash loads (West and Post 2002; Bhatt and Khera 2006).

If sugarcane trash used as mulch on the bare soils, then evaporation share decreased and thereby, trash partition more significant share of the evapotranspiration water to transpiration. Higher the transpiration, higher the inflow of the soil nutrients from the soil solution into the roots along with the water against the transpiration water (Jhanvi and Bhatt 2019). Therefore, under water-stressed conditions, proper trash management helps to attain good cane productivity. Trash also helps in improving the SOM, which further reported to have a favorable effect on the soil microorganisms by stimulating their respiratory rate, dehydrogenase activity, and arginine ammonification rate (Graham et al. 1999; Van Antwerpen et al. 2001) and reduces erosion losses to significant levels (Bhatt and Arora 2019) identifying this aspect, PAU already had a recommendation of application of trash at 50–62.5 q (quintal) ha^{-1} between rows after complete germination of canes by mid-April. Further, trash, as explained earlier, reduces soil temperature, weeds, evaporation, the incidence of shoot-borer, thereby improved cane yields both under rainfed as well as under irrigated conditions (PAU 2018-2019).

18.8.7 Compaction

Soil compaction is resulting from unavoidable traffic more particularly under good moisture conditions in many cane growing countries throughout the globe (Maud 1960). Soil compaction further resulted in increased bulk density, sealing of soil pores thereby hinders free air and water movements in the soil and root development of the sugarcane crop (Swinford and Boevey 1984; Swinford and Meyer 1985). The problem of soil compaction mostly prevailed in irrigated areas, where there may be drainage problems. Further, Johnston (1977) reported reduced macropore space between 0 and 80 mm deep, without any reduction in cane yields in the ratoon crop. Cross sub-soiling at 1.0 m spacing should be recommended after three to four years with sub-soiler. Further, planking also recommended crushing bigger soil clods, which further helps in breaking the hardpan, reducing bulk density, increasing root mass density, and increased water infiltration (PAU 2018-2019).

18.8.8 Salinity/Sodicity

Both saline and sodic conditions of the soils, representing higher salt contents, led to poor crop growth as it reduces the supply of the plant nutrients to the plants through soil solution (Vonder Meden 1966; Johnston 1977). Cause of this condition claims to be higher underground water table, as when saltwater comes up under the effect of the vapor pressure gradient through soil pores under capillary action, then the water evaporates and salts remained behind, finally led to the soil degradation. The build-up of salts in the soil as in South-Western Punjab is responsible for the decline in both attainable yield and quality of sugarcane (Culverwell and Swinford 1986).

$$\text{Clay site} - 2\text{Na} + \text{CaSO}_4.2\text{H}_2\text{O} \rightarrow \text{Clay site} - \text{Ca}^{2+} + \text{Na}_2\text{SO}_4$$

Reclamation of the sodic soils involves the application of the gypsum ($CaSO_4.2H_2O$), which reacts to replaces the Na ions attached to the clay sites and results in Na_2SO_4, which leached down below the rhizosphere. Generally, the gypsum is applied only when the pH of the soils is higher than 9.3, while soils reported with lesser than 9.3 pH are reclaimed with green manuring (PAU 2018-2019). Further, 50% of the calculated gypsum generally broadcasted if irrigation water is not sodic while dose recommended to 100% when irrigation water reported being sodic. Further, GypCal software developed by Central Soil Salinity Research Institute, Karnal, India, also helped to estimate the amount of gypsum to be applied at the affected site for having better land productivity (Arora and Bhatt 2016).

Salts also reported to affect the cane juice quality by reducing the purity and the percentage of sucrose (Fogliata and Aso 1965; Lingle and Wiegand 1997) because of accumulation of salts in the cane juice and due to Cl ion's inhibitory effect, and absorption of N and P, resulting in poor foliage (Kingston 1982). Concentrations of Na, potassium chloride (KCl) ions reported being higher in the cane juice. Poor quality of irrigation may also contribute indirectly to raw sugar ash levels. Further, the water quality of river sources becomes marginal for irrigation during the low flow period in the dry winter months (Meyer and Van Antwerpen 1995). An increase in Ca and Mg concentration levels in irrigation water and thus in soils and finally in the sugarcane juice observed after 20 years of irrigation with salt water (Meyer et al. 1998). Therefore, proper sugarcane cultivars must be screened out, which could bear this salt stress without hindering the juice quality.

18.9 Good Management Practices for Judicious Use of Sugarcane Fertilization

In general, there are four methods for judicious use of the sugarcane fertilization viz. correct amount, correct placement, correct timing, and leaf analysis. However, following is their brief discussion:

18.9.1 Correct Amount

Based on soil test reports and plant type viz. plant or ratoon, decides which nutrients and in which dose should be applied to harvest potential yields along with desired quality. Further**,** sugarcane crop *viz.* plant or ratoon both required different amounts of N-fertilizers at 150, and 225 kg N ha^{-1}, respectively, for plant and ratoon (PAU 2018-2019), hence, this thing must be kept in mind. Further, this dose is for the medium fertility soils, and again, farmers are advised to apply a 25% higher dose in soils reported with SOC lesser than 0.4% if SOC crosses 0.75%, then this dose might be reduced to 25%. Therefore, sugarcane N dosages varied as per different crop type weather plants or ratoon and SOC (%).

18.9.2 Correct Placement

The correct placement of fertilizers is the second most crucial factor which must be considered to have potential nutrient use efficiency in sugarcane crop. Placement of fertilizers near to row is the most efficient as then higher NUE observed due to lesser leaching losses. Further, splitting fertilizer dose can minimize off-farm impacts under certain conditions. Mostly in light-textured soils, splitting is adopted to improve the nutrient use efficiency.

18.9.3 Correct Timing

The correct timing of applying nutrients varies as per different nutrients as N runs, P walks, and K sits in soil. Therefore, N fertilizer application timing for the canes must be decided based on the N uptake behavior of the crop and the inherent soil fertility, which varied as per soil textural class, season, cultivar, and irrigation facilities. Nitrogen should be applied in two splits to plant while in three splits to ratoon crop, while P should be applied at the sowing time (PAU 2018-2019). Further, if crop encountered unfavorable conditions (rainfed conditions), then fertilization should be split accordingly to affect to the minimum.

18.10 Foliar Diagnosis for Timely Fertilization

Mostly, for sugarcane fertilization, mostly soil sampling and its analysis considered as the backbone for scheduling fertilization. However, mostly, these samples are not taken scientifically by taking care of all the precautions. Secondly, in soil testing labs, mostly of state governments, where because of lack of funds, chemicals are not updated. Most of the time, doing soil analysis is not perfect and is doing his job of soil analysis due to lack of alternative jobs. As a result, the aim is to achieve the target viz. the number of soil samples set for analysis. In all, quality is compromised to some extent. Hence, proper fertilization in sugarcane is sometimes missed, therefore during ratoon crop, leaf analysis might serve the purpose, and based on the leaf analysis report received from the soil lab, fertilizers must be applied to have potential and good quality yields.

18.11 Conclusions

"Sugarcane Resource Management" is generally ignored but most important for sustainable and climate smart sugarcane farming. Mostly farmers applied fertilizers as per their indigenous knowledge which might works during old times but proves a complete failure now due to dramatic change in the cane cultivars, soil fertility, and finally climate change. Therefore, proper resource management is most important for having good yields along with cane juice quality.

Due importance must be placed to the resource management viz. soil and water through advanced recommended sugarcane technologies which might vary from region to region. Selection of the proper cane cultivar must be made depending upon the soil textural class, underground water levels, salts extents, and agro-climatic conditions. Integrated nutrient management also played a role in improving the soil health in spite of improving the final cane juice quality. Along with chemical fertilization proper use of organic manures has a role to play. For sustainable sugarcane farming, farmyard manure (FYM) at 20 t ha^{-1} already recommended. Further, Azotobacter at 10 kg ha^{-1} also improves the soil plant and atmosphere interphase and supports the canes. Further, improved synchronicity between supply of nutrients and water and sugarcane demands for these resources could led to higher N use efficiency, higher cane yields with higher quality, lesser production of greenhouse gases and thus, helps in sustainable production of sugarcane in the region.

18.12 Future Perspectives

A number of future challenges are there in front of scientists as well as for the farmers to go for sustainable use of the resources for higher productivity as well as final juice quality. For this, problematic soils and poor water quality issues must be addressed and solved out by the soil scientists well in time. Plant breeder certainly has a very important role to play by identifying new potential parent lines and thus to bred some new hybrid sugarcane cultivars which could mitigate the adverse effects of the biotic as well as abiotic stresses and able to produce potential yields. Therefore, cane farmers today must be well equipped with the latest resource management techniques viz. soil test based soil fertilization, drip irrigation, seed treatment, new hybrids, proper ratoon management techniques, use of latest machines as tractor operated sugarcane cutter planter and mechanical harvester, pared row trench planting, bud chip technology, etc. Further, timely leaf, and plant analysis helps to identify deficiency of any nutrient deficiency which could be easily made up in time for getting potential yields. Mineralogical make-up of their soils, plant type weather plant or ratoon and if ratoon then how old the ratoon, cultivar selected weather early or mid-late, clay and organic content of their soils, irrigation water quality, and facilities in their hands must also be given due importance while planning programmes for the management of the resources. Only then the cane farmers in the region could improve their cane productivity, quality, and livelihoods on one side while, on other side could practice “sustainable sugarcane production” after mitigating global warming harmful effects by sustainable management of the resources based on the soil and leaf analysis.

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References

Alvarez R, Wutke ACP (1963) Fertilizing sugarcane. IX. Preliminary experiments with micronutrients. Bragantia 22:647–650

Anon (1997) Annual report (1996-97). Directorate of Water Management Res., Patna. P 102.

Arnon DI, Stout PR (1939) The essentiality of certain elements in minute quantity for plants with special reference to copper. Plant Physiol 14:371–375

Arora S, Bhatt R (2016) Resource conservation technologies (RCTs) for climate-resilient agriculture in the foothill of northwest Himalayas. In: Conservation agriculture: an approach to combat climate change in Indian Himalaya. Springer, Cham, pp 71–112. https://doi.org/10.1007/978-981-10-2558-7

Asokan S, Raj D (1984) Effect of nitrogen application on the nonsugar constituents of juice in cane. In: Proc 48th Ann Conv of Sugar Tech Assoc India. pp 137–140

Azeredo DF, Bolsanello J (1981) Effect of micronutrients in the production and quality of sugarcane in Rio de Janeiro, Espirito Santo and Minas Gerais (Zona da Mata). Prelim Stud Brazil Sugar 93:9–17

Bachchhav SM (1995) Scope and significance of fertigation technology in increasing sugarcane productivity. Nation. Sem. Relevance of micro irrigation in Sugarcane, 10–29th February, VSI Pune, Maharashtra, pp 226–233

Bangar AR, Chaudhary BC (2004) Nutrient mobility in soil, uptake, quality and yield of Suru sugarcane as influenced by drip fertigation in medium vertisols. J Indian Soc Soil Sci 52 (2):1473–1488

Barber (1931) History and development of sugarcane as a world crop. J Sugarcane 1:1–5

Batta RK, Sikka AK, Chaudhari SK (2005) Increasing water use efficiency through microirrigation systems in sugarcane: an overview. Proc. Nation. Sem. Relevance of Micro irrigation in Sugarcane, VSI Pune, Maharashtra, India

Berthelsen S, Hurney AP, Kingston G, Rudd A, Garside AL, Noble AD (2001) Plant cane response to silicated products in the Mossman, Innisfail and Bundaberg districts. Proc Aust Soc Sugar Cane Technol 23:297–303

Bhatt R (2016) Zero tillage for mitigating global warming consequences and improving livelihoods in South Asia. In: Wayne Ganpat (The University of the West Indies, Trinidad and Tobago) and Wendy-Ann Isaac (The University of the West Indies, Trinidad and Tobago) (ed.) Environmental sustainability and climate change adaptation strategies. pp 126–161. https://doi.org/10.4018/978-1-5225-1607-1.ch005

Bhatt R, Arora S (2019) Tillage and mulching options for conserving soil and water and improving livelihoods in foothills of lower Shiwaliks. J Soil Water Conserv 18(3):230–234

Bhatt R, Khera KL (2006) Effect of tillage and mode of straw mulch application on soil erosion losses in the sub-montaneous tract of Punjab, India. Soil Tillage Res 88:107–115

Bhatt R, Kukal SS (2016) An account of the indigenous technical knowledge (ITK) for soil and water conservation in sub-montaneous tract of Punjab, India. Indian Farm 66(6):23–25

Bhatt R, Sharma M (2013) Improving livelihood of farmers through front line demonstrations on oilseed and pulse crops in Kapurthala district of Punjab- A five year case study. In: Advances in experimental agriculture, vol 3. Agrotech Publishing Academy, Udiapur, pp 149–164

Bhatt R, Singh P (2020a) Soil fertility status of regional research station of Punjab Agricultural University, Kapurthala. Agri Res J PAU, Ludhiana

Bhatt R, Singh P (2020b) Inherent fertility status of University Seed Farm, Usman, Tarn Taran. J Agri Res, PAU, Ludhiana

Bhatt R, Kukal SS, Busari MA, Arora S, Yadav M (2016) Sustainability issues on rice-wheat cropping system. Int Soil Water Conser Res 4:68–83. https://doi.org/10.1016/j.iswcr.2015.12.001

Bhatt R, Singh P, Bansal SK (2019) Importance of potash for sugarcane cultivation in Punjab, India. In: Soil and water resources management for climate smart agriculture, global food and livelihood security. During November 5–9th, 2019 at NASC, Complex New Delhi

Bramely RGV, Wood AW, Cristaudo R (1996) Improving precision of phosphorus fertiliser recommendations for sugarcane. Proc Aust Soc Sugar Cane Technol 17:179–186

Brar MS, Mukhopadhyay DNS, Sharma P, Singh A (2008) Potassium: minerology and status in soils, and crop response in Punjab, India, Research bulletin of Punjab Agricultural University. Ludhiana and International Potash Research Institute, Horgen, pp 1–69. https://doi.org/10.3235/978-3-9523243-9-4

Bull (2000) The sugarcane plant. In: Manual of cane growing. Sugar Research Australia Ltd., Sydney, pp 71–84

Burkitt LL, Moody PW, Gourley CIP, Hannah MC (2000) A simple phosphorus buffering index for Australian soils. Aust J Soil Res 40:497–513

Cambria S, Boni PS, Strabelli J (1989) Estudos preliminares com micronutrientes – zinc. Piracicaba: Boletim Técnico Copersucar 46:12–17

Canegrowers (2002) Code of practice for sustainable cane growing in Queensland. Canegrowers, Brisbane, p 27

Chapman LS (1980) Long term responses in cane yields and soil analyses from potassium fertilizer. In: Proceedings of the 1980 Conference of the Australian Society of Sugar Cane Technologists. pp 63–68

Chatskikh D, Olsen JE (2007) Soil tillage enhanced CO_2 and N_2O emissions from loamy sand soil under spring barley. Soil Tillage Res 97(1):5–18

Chatterjee C, Nautiyal N, Dube BK (1998) Effects of potassium concentration on biochemistry, yield and sucrose concentration in sugarcane. Sugar Cane 5:12–15

Chauhan M (2019) Impact of climate change on sugarcane crop and remedial measures- a review. Pak Sugar J 34(1):15–22. https://doi.org/10.35380/sugar.034.01.0141

Clarke MA (1981) Potash: potential profits or problems. S Afr Sug J 43(10):18

Culverwell TL, Swinford JM (1986) Attempts at improving irrigation water quality in northern Zululand. Proc S Afr Sug Technol Assoc 60:168–171

Dang YP, Verma KS (1996) Nutrient management in sugarcane in Haryana State: key to improved sugar production. In: Wilson JR, Hogarth DM, Campbell JA, Garside AL (eds) Sugar cane research towards efficient and sustainable production. CSIRO Division of Tropical Crops and Pastures, Brisbane, pp 203–205

De Geus JG (1973) Sugar crops. In: de Geus JG (ed) Fertilizer guide for the tropics and subtropics, 2nd edn. Centre D'Ẽtude de L'Azote, Zurick, pp 136–182

de Souza RB, de Menezes JA, de Souza RD, Dutra ED, de Morais MA Jr (2015) Mineral composition of the sugarcane juice and its influence on the ethanol fermentation. Appl Biochem Biotechnol 175(1):209–222

Deshmukh AS, Shinde PP, Jadhav SB (1996) Fertigation under drip irrigation for sugarcane In: All India seminar on modern irrigation techniques, Bangalore. pp 217–219

Donaldson RA, Meyer JH, Wood RA (1990) Response to potassium by sugarcane, grown on base saturated clay soils in the Eastern Transvaal Lowveld. Proc S Afr Sug Technol Assoc 64:17–21

du Toit JL (1957) Fertiliser responses as revealed by the 3 x 3 x 3 fertilizer exploratory trials. Proc S Afr Sugar Technol Assoc 31:129–134

du Toit JL (1962) Available soil phosphate and yield responses in sugarcane. Proc S Afr Sugar Technol Assoc 11:101–111

Epstein E (1975) Mineral plant nutrition: principles and perspectives. Books Sci. Technol, Rio de Janeiro, p 341

Fageria NK, Baligar VC (2001) Lowland rice response to nitrogen fertilization. Commun Soil Sci Plant Anal 32:1405–1429

FAO (2012) FAOSTAT. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data/QC

FAO (2020) FAOSTAT. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data/QC

Fernanda F, Otto R, Vitti GC, do Vale DW, Miyake RTM (2017) Micronutrients application on cultivation of sugarcane billets. Afr J Agric Res 12(10):790–794. https://doi.org/10.5897/AJAR2016.11382

Filho JO (1985) Potassium nutrition of sugarcane. In: Munson RD (ed) Potassium in agriculture. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, pp 1045–1062

Fogliata FA, Aso PJ (1965) The effects of soil soluble salts on economy in sugarcane. SISSTA Sugar J 9(2):33–36

Franco HCJ, Mariano E, Vitti AC, Faroni EC, Otto R, Trivelin PCO (2011) Sugarcane response to boron and zinc in Southeastern Brazil. Sugar Technol 13:86–95

Gascho GJ (1983) The effect of nitrogen rate on four sugar cane varieties grown on sand. J Am Soc Sugar Cane Technol 2:84–87

Ghaffar A, Saleem MF, Fiaz N, Nadeem MA, Wains GM (2013) Yield and quality of sugarcane as influenced by different doses of potash and its time of application. Pak J Agric Sci 50(3):345–350

Glaz B, Ulloa MF (1995) Fallow and successive planting effects on sugarcane yields in Florida. J Am Soc Sugar Cane Technol 15:41–53

Goel AC, Kumar V, Dhindsa JPS (2005) Feasibility of drip irrigation in sugarcane at Haryana. In: Proc. Nation. Sem. Relevance of Micro irrigation in Sugarcane, VSI Pune, Maharashtra, India, pp 9–10

Gomes-Alvarez F (1974) Correlation between nutrient levels in sugarcane. J Faculty Agron Maracay 7:5–12

Graham MH, Haynes RJ, Meyer JH (1999) Green cane harvesting promotes accumulation of soil organic matter and an improvement in soil health. Proc S Afr Sugar Technol Assoc 73:53–57

Grimme H (1980) Factors controlling K availability to plants. In: Proc. Int Seminar on the Role of K in crop production, November 1979. Pretoria, South Africa

Gulati JML, Behera AK, Nanda S, Saheb SK (1998) Response of sugarcane (*Saccharum officinarum*) to potash. Indian J Agron 43:170–174

Hapase DG, Mankar AN, Salunkhe AN, Salunkhe VM, Singh G, Ilangantileke SG (1992) Techno-economic evaluation of drip irrigation for sugarcane crop. In: Proc Int Agric Eng Conf. 7–-10 December, Bangkok, Thailand. pp 897–904

Hapase DG, Deshmukh AS, Shinde PP (1993) Drip irrigation in sugarcane. Souvenir Nation Conf Use Plastics Agric. pp 30–38

Hartt CE, Kortschak HP, Forbes AV, Burr GO (1963) Translocation of 14C in sugarcane. Plant Physiol 38:305–318

Haynes RJ (1985) Principles of fertilizer use for trickle irrigation crops. Fert Res 6:235–225

Haynes RJ, Hamilton CS (1999) Effects of sugarcane production on soil quality: a synthesis of world literature. Proc S Afr Sugar Technol Assoc 73:46–52

Heck AF (1934) Phosphate fixation and penetration in soils. Soil Sci 37:343–355

Hermle S, Anken T, Leifeld J, Weisskop P (2008) The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions. Soil Tillage Res 98:94–105

Hetherington S, Asher CJ, Blamey FPC (1986) Tolerance of sugarcane to aluminium in soil and solution culture. Proc Aust Soc Sugar Cane Technol 8:63–68

Humbert RP (1968) The growing of sugarcane. Elsevier, Amsterdam

Irvine JE (1979) Variations in non-sucrose solids in sugar cane. I: potassium. Sugar J 41(5):28–30

Jangir CK, Kumar S, Meena RS (2019) Significance of soil organic matter to soil quality and evaluation of sustainability. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 357–381

Jhanvi S, Bhatt R (2019) Climate smart agricultural technologies in rice-wheat water stressed regions of Punjab, India- A review. J Appl Nat Sci 11(3):698–703

Johnston TD (1977) The measurement of mesophyll air space in lake and rape (*Brassica oleracea* L. and *B. napus* L.) leaves. Photosynthetica 11:311–313

Kakraliya SK, Jat RD, Kumar S, Choudhary KK, Prakash J, Singh LK (2017a) Integrated nutrient management for improving, fertilizer use efficiency, soil biodiversity and productivity of wheat in irrigated rice wheat cropping system in Indo-Gangatic Plains of India. Int J Curr Microb Appl Sci 6(3):152–163

Kakraliya SK, Kumar N, Dahiya S, Kumar S, Yadav DD, Singh M (2017b) Effect of integrated nutrient management on growth dynamics and productivity trend of wheat (*Triticum aestivum* L.) under irrigated cropping system. J Plant Dev Sci 9(1):11–15

Kakraliya SK, Kumar S, Kakraliya SS, Choudhary KK, Singh LK (2018) Remedial options for the sustainability of rice-wheat cropping system. J Pharm Phytochem 7(2):163–171

Keating BA, Bauld J, Hillier J, Ellis R, Weier KL, Sunners F, Connell D (1996) Leaching of nutrients and pesticides to Queensland groundwaters. In: Hunter HM, Eyles AG, Rayment GE (eds) Downstream effects of land use. Department of Natural Resources, City East, pp 151–163

Keating BA, Verburg K, Huth NI, Robertson MJ (1997) Nitrogen management in intensive agriculture: sugarcane in Australia. In: Keating BA, Wilson JR (eds) Intensive sugarcane production: meeting the challenges beyond 2000. CAB International, Wallingford, pp 221–242

Khosa TM (2002) Sources of potassium on growth, yield and quality of sugarcane. Better Crops Int 16(1):14–15

Kingston G (1982) Ash in first expressed cane juice at Rocky Point- Factors affecting the inorganic composition of juices. Proc Aust Soc Sug Cane Technol 52:11–17

Kingston G (1999) A role for silicon, nitrogen and reduced bulk density in yield response to sugar mill ash and filter mud/ash mixtures. Proc Aust Soc Sugar Cane Technol 21:114–121

Korndorfer GH (1989) Crescimento e distribuição do sistema radicular de cana-de-açúcar em solo LVA., Bol Tec Copersucar (Piracicaba). pp 47–89

Kozak M, Stêpieñ M, JOARDER AH (2005) Relationships between available and exchangeable potassium content and other soil properties. Polish J Soil Sci 38(2):179–186

Kumar S, Karaliya SK, Chaudhary S (2017) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. Int J Curr Microb Appl Sci 6 (3):142–151

Kumar S, Meena RS, Yadav GS, Pandey A (2017a) Response of sesame (*Sesamum indicum* L.) to sulphur and lime application under soil acidity. Int J Plant Soil Sci 14(4):1–9

Kumar S, Meena RS, Pandey A, Seema A (2017b) Soil acidity management and an economics response of lime and sulfur on sesame in an alley cropping system. Int J Curr Microb Appl Sci 6 (3):2566–2573

Lakholive BA, Kakde JR, Deshmukh VN, Daterao IH (1979) Nitrogen, phosphorus and potassium requirements of sugarcane (Co 1163) under Vidarbha conditions. Indian Sugar 29:149–151

Leverington KC, Sed JM, Burge JR (1962) Some problems in predicting potassium requirement of sugarcane. Proc Int Soc Sugar Cane Technol 11:123–130

Lindsay WL (1979) Chemical equilibria in soils. Wiley, New York

Lingle SE, Wiegand CL (1997) Soil salinity and sugarcane juice quality. Field Crop Res 54 (2):259–268

Madhuri NKV, Sarala NV, Kumar H, Rao M, Giridhar V (2013) Influence of micronutrients on yield and quality of sugarcane. Sugar Technol 15(2):187–191

Mahadkar UV, Raut RS, Shinde JB, Pawar DD, Gaikwad CB (2005) Response of pre-seasonal sugarcane to planting material, inter row spacing and fertilizer levels under drip irrigation. In: Proc. nation. sem. relevance of micro-irrigation in Sugarcane, 9–10th February 2005, VSI Pune, Maharashtra, India, pp 121–130

Mahendran S, Dhanalakhmi M (2003) Effect of crop geometry and drip fertigation on growth and yield of sugarcane crop. In: Souvenir: 65th Annual Convention of the Sugar Technologists' Association of India, 22–24th August, Bhubaneshwar, Orissa, Pub. Sugar Technologists' Association of India; New Delhi, India, pp 80–87

Mahendran S, Stephen J, Arun AC, Prabakaran P, Raja R (2005) Drip fertigation- potential technology for sugarcane yield maximization. In: Proc. Nation. Sem. relevance of micro-irrigation in sugarcane, 9–10th February 2005, VSI Pune, Maharashtra, India, pp 170–178

Malavolta E (1974) Mineral nutrition practice plants. Mimeog, Piracicaba

Malavolta E (1994) Nutrient and fertilizer management in sugarcane. International Potash Institute Bulletin No. 14. International Potash Institute, Basel

Marinho ML, Albuquerque GAA (1978) Calibration of extractable phosphorus in soils for sugarcane in Alagoas. Braz Proc XVI Congr ISSCT 2:1283–1292

Maud RR (1960) The compaction of sugar-belt soils at various moisture levels. Proc S Afr Sug Technol Assoc 34:154–156

McLaren RG, Cameron KC (1996) Soil science: Sustainable production and environmental protection, 2nd edn. Oxford University Press, Auckland

Meena H, Meena RS, Rajput BS, Kumar S (2016a) Response of bio-regulators to morphology and yield of cluster bean [*Cyamopsis tetragonoloba* (L.) Taub.] under different sowing environments. J Appl Nat Sci 8(2):715–718

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016b) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena RS, Kumar V, Yadav GS, Mitran T (2018) Response and interaction of *Bradyrhizobium japonicum* and Arbuscular mycorrhizal fungi in the soybean rhizosphere: a review. Plant Growth Regul 84:207–223

Meena RS, Kumar S, Bohra JS, Lal R, Yadav GS, Pandey A (2019a) Response of alley cropping-grown sesame to lime and sulphur on yield and available nutrient status in an acidic soil of Eastern India. Energy Ecol Environ 4:65–74. https://doi.org/10.1007/s40974-019-00113-w

Meena RS, Kumar S, Yadav GS (2019b) Soil carbon sequestration in crop production. In: Meena RS (ed) Nutrient dynamics for sustainable crop production. Springer, Cham, pp 1–39. https://doi.org/10.1007/978-981-13-8660-2_1

Meena RS, Lal R, Yadav GS (2020) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Mellis EV, Quaggio JA, Cantarella H (2008) Micronutrients. In: Dinardo-Miranda LL, Vasconcellos ACM, Landell MGA (eds) Sugarcane. Agron. Institute, Campinas, pp 331–336

Mellis EV, Quaggio JA, Teixeira LAJ, Becari IBC, Days FLF, Cantarella H (2010) Residual effect of micronutrients in sugarcane. In: FERTBIO 2010 Guarapari-ES. Fertbio 2010. Tec Art Publishing House, Guarapari

Meyer M (2013) Sugarcane nutrition and fertilization. In: Meyer JH, Turner PE, Rein P, Mathias K (eds) Good management practices for the cane industry edition, 1st edn. Bartens, Berlin, pp 133–180

Meyer JH, Dicks E (1979) The results of P fertilizer trials conducted in the Natal Midlands. Proc S Afr Sugar Technol Assoc 53:182–186

Meyer JH, van Antwerpen R (1995) Trends in water quality of selected rivers in the South African sugar industry. Proc S Afr Sugar Technol Assoc 69:60–68

Meyer JH, Wood RA (1989) Factors affecting phosphorus nutrition and fertilizer use by sugarcane in South Africa. Proc S Afr Sugar Technol Assoc 63:153–158

Meyer JH, Wood RA, Leibbrandt NB (1986) Recent advances in determining the N requirement of sugarcane in the South The concepts of minimum tillage in sugarcane African sugar industry. Proc S Afr Sugar Technol Assoc 60:205–211

Meyer JH, Harding R, Rampersad AL, Wood RA (1998) Monitoring long term soil fertility trends in the South African sugar industry using the FAS analytical database. Proc S Afr Sugar Technol Assoc 72:61–68

Meyer JH, Schumann AW, Schroeder BL, Wood RA, Rampersad AL (1999) Review of research on the micronutrient requirement of sugarcane in South Africa. Proc S Afr Sugar Technol Assoc 73:63–71

Mitscherlich EA (1909) Das Gesetz des Minimum und das Gesetz des alsnehmenden Bodenetrages. Landw Jahrb 38:537–552

More NB, Wandre SS, Hasabmis AB, Patil BR (1995) Response of sugarcane cultivar Co-7527 to different levels of NPK fertilizer. J Maharashtra Agric Univ 20(2):198–200

Nagarajah S (2006) The effect of potassium deficiency on stomatal and cuticular resistance in tea (*Camellia sinensis*). Physiol Plant 47(2):91–94

Ng Kee Kwong KF, Deville J (1994) Application of 15N-labelled urea to sugar cane through a dripirrigation system in Mauritius. Fert Res 239:223–228

Nixon DJ (1992) The impact of fallowing and green manuring on properties and the productivity of sugarcane in Swaziland. Ph.D. dissertation, University of Reading, England

Nixon DJ, Simmonds LP (2004) The effects of fallowing and green manuring practices on soil physical properties and the growth of sugarcane. Exp Agric 40:127–138

Obreza TA, Anderson DL, Pitts DJ (1998) Water and nitrogen management of sugarcane on sandy, high water-table soil. Soil Sci Soc Am J 62:992–999

Olalla L, Jurado F, Navarro E, Mira A (1986) Analysis of the lack of response to fertilizer application in sugar cane grown at Churriana (Malaga). Sugar Cane 4:9–10

Orlando Filho J, Rossetto R, Casagrande AA (2001) Sugarcane In: Ferreira ME, Cruz MC, Raij BV, Abreu CA (Ed.) Micronutrients and toxic elements in agriculture. CNPQ/Fapesp/Potafós, Jaboticabal, p 600

Paneque VM, Martinez MA, Gonzalez PJ (1992) Study of potassium levels in three sugarcane varieties grown on compacted red ferralitic soil. Cultivos Trop 13:5–8

Parikh MM, Savani NG, Srivastava PK, Avadaria JD, Thanki JD, Shah GB, Holer GG, Desai SG (1996) Response of various crops to micro-irrigation, mulching and fertigation. In: Proc. All India Sem Modern Irri Tech 26-27 July, Bangalore, India, pp 206–212

Parsons JW (1962) Soil organic matter. Nature 194(4826):324–325. https://doi.org/10.1038/194324b0

Patil GD, Yelwande AJ, Chaudhari RD (2001) Nitrogen fertilization to sugarcane: prospects and retrospect. J Maharashtra Agric Univ 26(1-3):156–158

PAU (2018-2019) Package of practices for crops of Punjab. Rabi 2018-19, released by Punjab Agricultural University, Ludhiana

Platford GG (1979) Research into soil and water losses from sugarcane fields. Proc S Afr Sug Technol Assoc 50:152–156

Prasad RAO M, Sivanappan RK, Naidu KM (1983) Evaluation of irrigation methods for its economy m Sugarcane. In: Proceedings of second National Seminar on Drip Irrigation held at T.N.A.U., Coimbatore, India during March 5–6, 1983

Prasad R, Prasad US, Sakal R (1996) Effect of potassium and sulfur on yield and quality of sugar cane grown in calcareous soils. J Potassium Res 12:29–38

Pribyl DW (2010) A critical review of the conventional SOC to SOM conversion factor. Geoderma 156(3-4):75–83. https://doi.org/10.1016/j.geoderma.2010.02.003

Rabindra S, Swamygowda SN, Devi TG (1993) Long term effect of fertilizers on sugarcane. Curr Ther Res 22:6–8

Ramanujam T, Venkataramana S (1999) Radiation interception and utilization at different growth stages of sugarcane and their influence on yield. Indian J Plant Physiol 4:85–89

Rani K, Sharma P, Kumar S, Wati L, Kumar R, Gurjar DS, Kumar D, Kumar R (2019) Legumes for sustainable soil and crop management. In: Meena RS, Kumar S, Bohra JS, Jat ML (eds) Sustainable management of soil and environment. Springer, Cham, pp 193–215. https://doi.org/10.1007/978-981-13-8832-3_6

Raskar BS, Bhoi PG (2001) Productivity of sugarcane as influenced by planting techniques and sources of fertigation under drip irrigation. Indian Sugar 50(11):801–810

Regina K, Alakukku L (2010) Greenhouse gas fluxes in varying soils types under conventional and no tillage practices. Soil Tillage Res 109:144–152. https://doi.org/10.1016/j.still.2010.05.009

Rice RW, Gilbert RA, Lentini RS (2002) Nutritional requirements for Florida sugarcane. Florida Coop. Ext. Ser., UF/IFAS, Doc. SS-ARG-228. Univ. of Fla., Inst. Food Agric. Sci., Gainesville

Rozeff N (1990) A survey of south Texas sugarcane nutrient studies and current fertilizer recommendations derived from this survey. J Am Soc Sugar Cane Technol 10:26–33

Sachan RS, Ram N, Gupta RA (1993) Effect of soil and applied nitrogen, phosphorus and potassium on the yield of planted and ratoon crop of sugarcane in a Mollisol of Uttar Pradesh. Indian Sugar 42:769–773

Samuels G (1969) Major element nutrition with respect to foliar diagnosis. In: Samuels G (ed) Foliar diagnosis of sugarcane. Adams Press, Chicago, pp 217–243

Santo LT, Nakahata MH, Schell, VP (2000) Calcium and liming trials from 1994 to 1998 at HC&S. Technical supplement to Agronomy Report 83, Hawaiian Agricultural Research Centre. pp 1–20

Selvaraj PK, Asokaraja N, Manickasundram P, Muthuchamy I, Mohanmed Ali A (1997) Drip Irrigation for sugarcane. Indian Farm 46(10):23–24

Sharma P, Meena RS, Kumar S, Gurjar DS, Yadav GS, Kumar S (2019) Growth, yield and quality of cluster bean (*Cyamopsis tetragonoloba*) as influenced by integrated nutrient management under alley cropping system. Indian J Agric Sci 89(11):1876–1880

Shinde SH, Dahiwalkar SD, Bhoi PS (1998) Effect of fertigation through drip irrigation and planting technique on yield and quality of Suru sugarcane. In: Proc. Nation. Sem. Irrigation Water Management for Sugarcane, 5–6 June, VSI, Manjari (BK), Pune, pp 59–69

Shinde SH, Dahiwalkar SD, Berad SM (1999) Influence of planting techniques and fertigation through drip on yield, quality and economics of sugarcane. J Maharashtra Agric Univ 24 (3):276–278

Siqueira OJ, Silveira JF, Guedes GA (1979) Effect of micronutrients in the presence and absence of lime in agricultural yield and quality of sugarcane juice (plant cane). Braz Sugar 94(5):77–80

Sobral AF, Weber H (1983) Mineral nutrition of sugarcane (micronutrients). In: Son Orlando F (ed) Nutrition and fertilization of sugarcane in Brazil. IAA/Planalsucar, Piracicaba, pp 103–122

Srivastava SC, Suarez NR (1992) Sugarcane. In: Wichmann W (ed) World fertilizer use manual. BASF AG, Ludwigshafen, pp 257–266

Stevenson DM, McGrath GT, Statham MK (1970) A potash survey in the Pioneer Mill area. Proc Qld Soc Sug Cane Technol 37:39–49

Sudama S, Tiwari TN, Srivastava RP, Singh GP, Singh S (1998) Effect of potassium on stomatal behaviour, yield and juice quality of sugarcane under moisture stress conditions. Ind J Plant Physiol 3:303–305

Swinford JM, Boevey TMC (1984) The effects of soil compaction due to infield transport on ratoon cane yields and soil physical characteristics. Proc S Afr Sug Technol Assoc 60:198–203

Swinford JM, Meyer JH (1985) An evaluation of a nuclear density gauge for measuring in-field compaction in soils. Proc S Afr Sug Technol Assoc 59:218–224

Syers JK (1998) Soil and plant potassium in agriculture. Proceedings No. 411. The International Fertilizer Society, York, p 32

Taiz L, Zeiger E, Santarém ER (2004) Plant physiol, 3rd edn. Artmedo, Porto Alegre, p 719

Thompson GD (1988) The composition of plant and ratoon cane crops of variety N_{14} at Pongola. Proc Int Soc Sug Cane Technol 17:182–195

Thompson GD (1991) The growth of sugarcane variety N14 at Pongola. Mount Edgecombe Research Report No. 7. Published by the South African Sugar Association Experiment Station, Mount Edgecombe, South Africa

Thorburn PJ, Park SE, Biggs IM (2003) Nitrogen fertilizer management in the Australian sugar industry: strategic opportunities for improved efficiency. Conference of the Australian Society of Sugar Cane Technologists held at Townsville, Queensland, Australia, 6-9 May 2003, p 22

Tilib MAE, Elnasikh MH, Elamin EA (2004) Phosphorus and Potassium fertilization effects on growth attributes and yield of two sugarcane varieties grown on three soil series. J Plant Nutr 27 (4):663–699. https://doi.org/10.1081/PLN-120030375

Tripathi DK, Singh S, Singh S, Mishra S, Chauhan DK, Dubey NK (2015) Micronutrientsand their diverse role in agricultural crops: advances and future prospective. Acta Physiol Plant 37 (7):1–14

Truog E (1948) Lime in relation to availability of plant nutrients. Soil Sci 65:1–7

Vaishnava VG, Shelke DK, Bharambe PR (2002) Drip Irrigation and fertigation for sugarcane in deep black soils, Paper number 022203, ASAE Annual Meeting. Amer. Soc. Agric. Biol. Eng., St. Joseph Michigan. www.asabe.org.

Vale DW, Prado RM, Cantarella H, Fonseca IM, Avalhaes DC, Barbosa MP (2012) Nitrogen effects on the yield of sugar cane harvested whithout the previously husking plants by fire. J Plant Nutr 2:130–140

Van Antwerpen R, Meyer JH, Turner PET (2001) The effects of cane trash on yield and nutrition from the long term field trial at Mount Edgecombe. Proc S Afr Sug Technol Assoc 75:235–241

Van Antwerpen R, Haynes R, Meyer JH, Hlanze D (2003) Assessing organic amendments used by sugarcane growers for improving soil chemical and biological properties. Proc S Afr Sug Technol Assoc 77:293–299

Varma D, Meena RS, Kumar S (2017) Response of mungbean to fertility and lime levels under soil acidity in an alley cropping system of Vindhyan Region, India. Int J Chem Stud 5(4):1558–1560

Verma RR, Srivastva TK, Singh KP (2014) Soil macro-and micro nutrient status in sugarcane growing soils of Haridwar district, Uttarakhand (India). Ind J Sugarcane Tech 29(02):72–76

Vonder Meden EA (1966) Note on salinity limits for sugarcane in Natal. Proc S Afr Sug Technol Assoc 40:86–89

Vuyyuru M, Sandhu HS, McCray MJ, Raid RN, Erickson JE (2019) Effects of nitrogen fertilization and seed piece applied fungicides on establishment, tiller dynamics, and sucrose yields in successively planted sugarcane. Agronomy 9(387):1–22. https://doi.org/10.3390/agronomy9070387

Weigel A, Meyer JH, Moodley S, Tonsing W, Nixon D, Vanden Berg M (2008) Drip irrigated sugarcane response to applied nitrogen in the dry form and by fertigation in late and early season cycle. Proc S Afr Sug Technol Assoc 82:333–342

West TO, Marland G (2002) Net carbon flux from agricultural ecosystems: methodology for full carbon cycle analyses. Environ Pollut 116:437–442

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci Soc Am J 66:1930–1946

Wiley N (2018) Soil pH. In: Environmental plant physiology. Taylor and Francis Group, Milton Park. https://doi.org/10.1201/9781317206231-10

Wood GH (1962) Some factors influencing starch in sugarcane. Proc S Afr Sug Technol Assoc 36:123–135

Wood RA (1964) Analogous nitrogen mineralisation effects produced by soils under grass leys and sugar cane. Int Congr Soil Sci 8:255–260

Wood RA (1972) Factors affecting nitrogen utilisation by sugarcane in South Africa. PhD Thesis Department of Soil Science, University of Natal, Pietermaritzburg, Republic of South Africa

Wood RA (1982) Nutrition and cane quality. S Afr Sug Agron Ass. Unpub pap S Air Sug Ind Agron Ass Yang SJ and Chen JM 1981. A review of fertilizer trials carried out by the Fiji Sugar Corporation between 1977 and 1987. Taiwan Sugar 38:19–24

Wood RA (1990) The roles of nitrogen, phosphorus and potassium in the production of sugarcane in South Africa. Fert Res 26:87–98

Wood RA, Meyer JH (1986) Factors affecting potassium nutrition of sugarcane in South Africa. Proc S Afr Sugar Technol Assoc 60:198–204

Wood AW, Safigna PG, Prammanee P, Freney JR (1990) Loss of nitrogen from urea applied to sugarcane trash in north Queensland. Proc Int Soc Sugar Cane Technol 20:481–488

Xiao Z, Liao X, Guo S (2017) Analysis of sugarcane juice quality indexes. J Food Qual 3:1–6. https://doi.org/10.1155/2017/1746982

Linking Sustainability and Competitiveness of Almond Plantations Under Water Scarcity and Changing Climate

19

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Abstract

Climate change, water resources depletion, or land degradation and abandonment are some constraints to overcome within the new paradigm of achieving competitive and sustainable agriculture. Within the possible strategies, the introduction of drought-tolerant crops with high profitability, and the implementation of water-saving strategies such as deficit irrigation (DI) should be considered. Within the crop possibilities, almond (*Prunus dulcis* Mill.) would be an excellent alternative under water scarcity and climate change scenarios. However, it is essential to reach an equilibrium between crop management and water availability, defining its water requirements and the relationships between irrigation needs and the agronomical practices. Once done, adaptation strategies to water scarcity should be considered, especially in those cases of lack to cover the total irrigation needs by DI practices. In this agreement, the success of these strategies will depend on the proper knowledge respect to crop phenological development and the assessment of physiological status using different available tools. Thus, different crop physiological responses to water stress will be observed and different taking decisions should be considered. Finally, implementing water-saving strategies will be done not only from the perspective of preserving maximum yields but also for product quality improvements, and hence providing a final added value.

Keywords

Crop management · Deficit irrigation · Nut quality · Physiological response · Thermography

Abbreviations

A/C_i	Relationship between photosynthetic rate and internal concentration of C
A_N	Photosynthetic rate
DI	Deficit irrigation
E	Transpiration
ET_C	Crop evapotranspiration
EU	European Union
FI	Full irrigation
g_S	Stomatal conductance
ha	Hectare
I_G	Index of relative stomatal conductance
K_C	Crop coefficient

kg	Kilogram
LFDI	Low-frequency deficit irrigation
mg	Milligram
MPa	Megapascal
MUFA	Monounsaturated fatty acid
NWSB	Non-water stress baseline
ppm	Parts per million
PRD	Partial root drying
PUFA	Polyunsaturated fatty acid
RDI	Regulated deficit irrigation
Rubisco	Ribulose-1,5-bisphosphate carboxylase/oxygenase
SDI	Sustained deficit irrigation
SFA	Saturated fatty acid
T_C	Canopy temperature
VPD	Vapour pressure deficit
WSB	Water-stress baseline
WUE_i	Intrinsic water use efficiency
ΔT	Difference between canopy and air temperature

19.1 Introduction

There is a consensus about the weak management of water resources in the Mediterranean areas of southern Europe, and the need of reaching an equilibrium between rural development, food security, and environmental protection (Iglesias and Buono 2009; Iglesias et al. 2011). Climate change will significantly affect the ecological equilibrium, with even higher challenges concerning the sustainable management of natural resources, these being between the main constraints to be solved (Iglesias and Garrote 2015; Lakhran et al. 2017; Kumar et al. 2016, 2017a, b).

Different works have been recently developed to assess the effects of climate change and its impact on the agricultural systems (Bindi and Olesen 2011; Lobell and Gourdji 2012; Korres et al. 2016; Webber et al. 2018; Meena et al. 2019). On overall, these studies have remarked the unsustainability of the current management systems of water at farm level, especially in those regions of south Europe (Gleeson et al. 2012; Garrote et al. 2015), with particular emphasis in South Spain (Ruiz-Ramos and Mínguez 2010; Ruiz-Ramos et al. 2018). In this agreement, Mediterranean countries of southern Europe will be significantly affected in the future climate change scenarios, with significant increases in the average air temperature (>2–4 °C), more heat waves events, or decrease in precipitations (~30%), which will increase the risks of drought and biodiversity losses, or decreases in crop yields (EEA 2017).

Moreover, climate change will promote not only substantial changes about the natural resources management, but also in the crop phenological development; these changes being associated with a shortening in the crops cycles, an earlier flowering, and a higher heat and water stress (Gabaldón-Leal et al. 2017; Lizaso et al. 2018; Lorite et al. 2018). In this regard, there are three key factors that ultimately will cause significant changes in crops development: higher temperatures, water resources depletion for crop development (−15 to −25%) (Iglesias et al. 2012), and the increase of atmospheric carbon dioxide (CO_2) (Rani et al. 2019; Kumar et al. 2020), which could reach values close to 700 ppm (Flexas et al. 2014; Korres et al. 2016).

Concretely, for the case of almond (*Prunus dulcis* Mill.) and the main effects promoted by climate change, the works developed are relatively scarce; and almost all of them are related to the temporal variations of the different phenological periods, as it has been recently reported by Gabaldón-Leal et al. (2017) and Lorite et al. (2018) in olives. Moreover, according to De Ollas et al. (2019), phenological changes on fruit trees derived from climate change will probably determine not only the yield but also the fruit quality and marketability. Thus, it is expected that higher temperatures during the flowering and fruit-setting period could promote a massive flower dropping, with significant reductions in the yield, as it has been suggested by other authors such as Albrigo and Saúco (2004) and Iglesias et al. (2007).

In relation to the increase of CO_2, currently, there is no clear consensus about the interactions between the increasing atmospheric temperature and CO_2 concentration, and the expected water scarcity scenarios (Zandalinas et al. 2017). Authors such as Medlyn (2011), Flexas et al. (2014) have suggested that the increase of CO_2 content could be accompanied with a reduction in the crop transpiration (E) levels, and hence higher intrinsic water-use efficiency (WUE_i). On the contrary, some authors have observed in plants grown under high CO_2 content during long-term periods, some modifications in the parenchymal of mesophyll and the chloroplasts, reflecting variations in the photosynthetic rate (A_N), alterations in the ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) activity and during the photorespiration (Vu et al. 2002; Vu 2005). Likewise, nowadays, there is not too much information about the physiological interactions promoted by the increasing of CO_2 content and modifications in the air temperature and water stress situations. All these constraints and challenges related to the sustainability and competitiveness of irrigated agriculture, more concretely for the case of almonds, will be discussed in this chapter.

19.2 Almond Crop as a Suitable Alternative Under Climate Change Scenarios

The European Environment Agency has recently described the main impact derived from climate change, among them, significant alterations in the average temperature, a higher frequency of extreme events, and the rainfall irregularity (EEA 2019; Meena et al. 2020b). These constraints will affect not only to the crops final yield and its components, but also put the detrimental effects in the remaining processes such as the storage, transport conditions, and/or product transformation. Moreover, these effects are not appearing in the same way along the European Union (EU), the Mediterranean countries being the most affected, especially the southern regions. As a consequence, a progressive deterioration of rural areas, and a descend in terms of

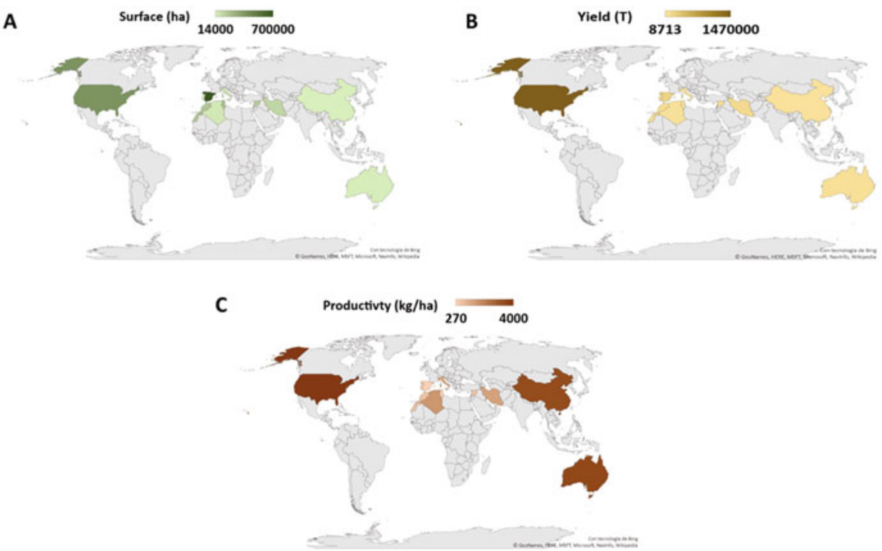


Fig. 19.1 Almond surface (**a**), yield (**b**), and productivity (**c**) worldwide

productivity of agroecosystems, and, ultimately, the land abandonment are expected (IPCC 2018). In this sense, the agricultural sector will require a rapid adaptation with the aim of ensuring a sustainable production throughout crop management practices at the farm level (EC 2018).

As a response, the EU have included as the primary objective for the new Common Agricultural Policy 2021–2027, the promotion of practices to ensure the adaptation and mitigation to the climate change; throughout investments, incentives, and improving the final returns (IEEP 2018). According to Iglesias and Garrote (2018), under these environmental conditions, the use of adapted crops to arid and semi-arid environments or the use of tolerant cultivars to drought must be seriously considered. Also, the usage of different techniques related to precision agriculture and the improvement the water-use efficiency is within the whole of the required actions. In this sense, at the farm level, the implementation of these strategies will also encourage for the sustainability, profitability, and viability of Mediterranean agroecosystems. These actions are even more necessary in those regions where the agricultural intensification have promoted land degradation in many rural areas as south Spain (Ibarrola et al. 2017; Tójar et al. 2017).

Almond does not represent a novelty crop in the south of Europe, this being widely cultivated in many Mediterranean countries such as Italy, Greece, Syria, Tunisia, Argelia, and Morroco, although, up today, Spain is the most representative country in terms of surface worldwide (Fig. 19.1a). However, these data contrast with those related to the crop productivity (in terms of the surface), the USA and Australia being the most relevant producers (Fig. 19.1b, c), providing 80% of the global market (FAOSTAT 2018).

Moreover, the USA, with a surface close to 400,000 ha, is able to reach an annual production of almonds close to 1.5 million tonnes, with an average productivity between 3500 and 4000 kg ha^{-1}. By contrast, Spain, with 700,000 ha, produces ~200,000 tonnes and the average productivity would be close to 300 kg ha^{-1} (FAOSTAT 2018). These values are related to the water availability because almond has been traditionally cultivated under rainfed conditions in marginal areas of south Spain (Arquero 2013). Recently, a significant increase in the surface devoted to this crop has been observed, especially in irrigated areas traditionally occupied by other species (CAPDR 2016). This fact has been primarily associated with the relevant increases in the almond prices during 2014–2016, and after this, price stability around to 6 euros per kg (OPM 2019).

As a response, this crop has been progressively introduced under irrigated conditions, to be developed under those traditional strategies of management designed in those countries where the maximum productivity is reached. Under this new paradigm, it is worth to consider the possibilities and capability of simulating these viable management strategies under the current conditions registered in Mediterranean countries such as Spain.

In the case of almond, in spite of being a drought-tolerant crop, water availability is the most limiting factor to reach maximum yield values in terms of number and size of fruit (Goldhamer and Fereres 2017). It has been shown that optimum water requirements for the almond crop would range between 9000 and 13,500 m^3 ha^{-1}, depending on location, rootstock, variety, canopy size, and tree spacing (López-López et al. 2018a; Goldhamer and Girona 2012). Thus, considering the water requirements of the almond, its acceptance as an alternative crop would be exclusively justified within an equilibrium between the crop management and the water availability, focusing the efforts in search of equilibrium among agricultural activity, competitiveness, and environmental protection (García-Tejero et al. 2014). Thus, exclusively from the acceptance limitations of production systems, and the delusion of each producer, it will be possible to maximize the final yield, the fruit quality, and redesigning the irrigated agriculture for environmental constrains under climate change context.

19.3 Linking Almond Water Requirements and Crop Management

According to Allen et al. (1998), almond water requirements are defined to cover the evapotranspiration losses under optimum conditions; that is, a disease-free crop, without nutritional deficiencies and proper soil characteristics. Total almond water requirements have been intensely studied under very different conditions (Girona 2006; Sanden et al. 2012; García-Tejero et al. 2015; Espadafor et al. 2015, among others). Figure 19.2 shows the monthly crop coefficient (K_c) values obtained for almond crops under different conditions. Overall, comparing the K_C values obtained in the first experiences (four decades ago) and those more recently developed, it can be concluded that the maximum K_C values, which were registered during the

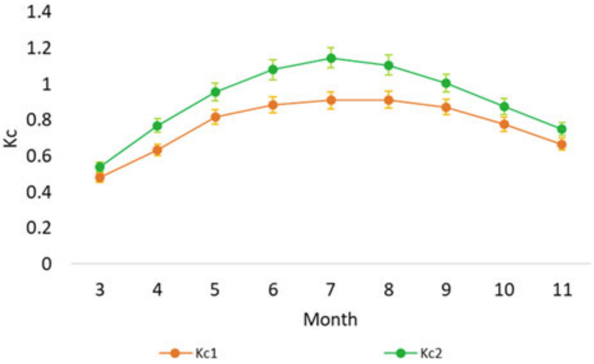


Fig. 19.2 Comparison of two series of almond K_C. K_{C1} was obtained as the average of the values reported by Doorenbos and Pruitt (1977); Goldhamer (1989); and Allen et al. (1998). K_{C2} was obtained as the average of the values reported by Sanden et al. (2012); Goldhamer and Girona (2012); and García-Tejero et al. (2015)

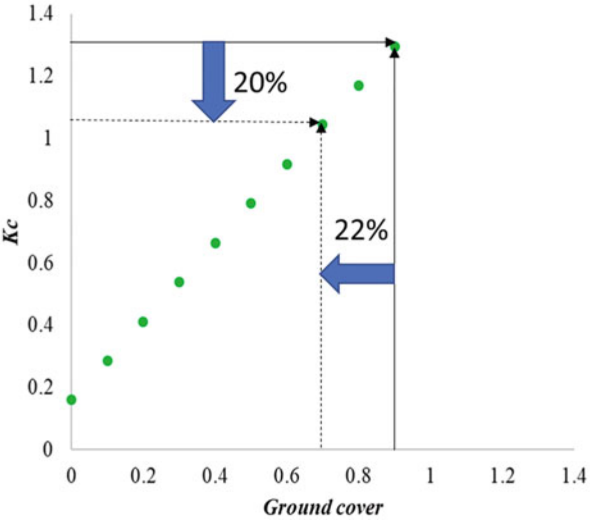
kernel-filling and harvesting stages, have progressively increased with time. In this sense, observing the maximum K_C values reported by Doorenbos and Pruitt (1977) and Allen et al. (1998) during the kernel-filling period, and those obtained in more recent studies as those conducted by Sanden et al. (2012); García-Tejero et al. (2015); Goldhamer and Fereres (2017). It can be observed an increase of K_C from 0.9 to 1.2, which would suggest crop water requirements 30% higher for the most recent scenarios. These variations are a direct response to the intensification of the productive almond systems, with practices of minimum pruning (higher canopy volumes) and reductions in the plant spacing (higher plant densities (Steduto et al. 2012)). As a response, the irrigation requirements of almonds have significantly increased. The actual annual water requirements in mature almond trees in California would be close to 13,000 m^3 ha^{-1} (Goldhamer and Fereres 2017) or for the case of South Spain, close to 8000 m^3 ha^{-1} (García-Tejero et al. 2018a; López-López et al. 2018a); about 50% higher than those estimated three decades ago in orchards with yields that were practically half of current yields (~3500–4000 kg ha^{-1}) (Goldhamer and Viveros 2000; Goldhamer and Fereres 2017; García-Tejero et al. 2018a).

Within a context of water scarcity scenarios, it is noteworthy to consider those strategies focused on reaching an equilibrium between the crop management and water requirements. The first experiments focused on establishing the relationships between canopy size and crop water requirements were conducted by Fereres et al. (1982), and more recently, other authors as Ayars et al. (2003), Fereres et al. (2012) have discussed the effects of canopy volume in the irrigation requirements. In recent times, Schwankl and Prichard (2017) have reported a single function for the relationship between the percentage of ground shading and K_C, concluding that on average, evapotranspiration increases at a rate approximately 1.26 times (Eq. 19.1) the percent of ground shading (Fig. 19.3).

$$K_C = 1.2626GC + 0.16 \tag{19.1}$$

where K_C is the crop coefficient and ground cover is the percentage of cast shaded area by the tree canopy.

Fig. 19.3 Relationship between the ground cover and crop coefficient (K_c). As an example, a ground cover reduction of 22% would allow a crop water requirement reduction close to 20%



According to this, canopy size directly determines the almond E, and hence canopy volume would be a key factor to be adequately controlled when almond trees are going to be grown under water scarcity scenarios. Moreover, this relationship between the canopy volume, intercepted radiation, and crop E was intensely studied by Espadafor et al. (2015), who concluded that there is a constant relationship between the E coefficient and fraction of intercepted radiation (fIR).

These considerations should be considered when this crop is going to be developed in irrigated areas where water allocations are going to be below the total crop water requirements. In this regard, Johnson et al. (2000, 2001) argued the importance of radiation interception by tree canopies to determine the K_C values. Furthermore, different authors concluded that radiation interception would be the main factor to determine the ratio ET_C/ET_0 (crop evapotranspiration/reference evapotranspiration) in deciduous orchards such as peaches (Ayars et al. 2003), vineyards (Williams and Ayars 2005), or almonds (Espadafor et al. 2015), as it has been previously discussed.

19.4 Deficit Irrigation Strategies to Achieve Sustainable and Competitive Almond Yields Under Water Scarcity Scenarios

Almond has been traditionally considered as a proper alternative under drought scenarios, and for this reason, its development has been traditionally associated with rainfed conditions in many areas of south Spain (Torrecillas et al. 1988, 1996). Within the advantages of this crop would be its pronounced phenology, which promotes different results depending on the phenological period in which the water stress is imposed. In this agreement, many authors have reported the advantages and opportunities of deficit irrigation (DI) in the almond crop, this being able of obtaining competitive yields under moderate-to-severe situations (Table 19.1).

Moreover, integrating the traditional crop management practices (such as pruning system and intensity) with DI strategies is essential to reach an equilibrium between water allocations and sustainable and competitive yields. When a DI strategy applied, the most probable results will be associated to yield reductions, although the main success will be focused on reaching maximum water savings minimizing the yield reductions (García-Tejero et al. 2014). Even more, if possible, improving some fruit properties related to its chemical composition, healthy compounds, or sensory profile and the consumer acceptance should be considered (Lipan et al. 2018).

However, its yield response under non-and-irrigated conditions has been reported as tenfold (Girona 1992). Gutiérrez-Gordillo et al. (2019a) reported that the implementation of DI in almond plantations resulted as a suitable strategy to obtain competitive yield without committing the fruit quality. Many authors have reported the advantages of moderate DI treatments, such as controlling an excessive vegetative growth, reducing fungal affections, or easing the fruit harvesting and almond processing (Teviotdale et al. 2001; Goldhamer et al. 2006).

Moreover, different vital factors should be considered when a DI strategy is going to be imposed, such as the irrigation strategy, crop phenological development, or defining threshold values of some physiological indicators (Fig. 19.4).

For the case of almond, its sharp phenology allows differentiating the main effects of DI, depending not only on the intensity, but mainly its phenological development (Fig. 19.5), characterized by different stages (dormant, bloom (Stage I), fruit growth, and vegetative development (Stage II), kernel-filling with dry-matter accumulation and pre-harvest (Stage III), and post-harvest, when reserves accumulation and buds differentiation occurs before leaf-fall) (Doll 2009).

In Mediterranean countries, almond flowering and its vegetative development occur in the first months of the year the harvesting occurring between the end of July and September, depending on the cultivar and the registered climatic conditions (Goldhamer and Girona 2012). Flowering and canopy growing take place almost simultaneously, once the crop has accumulated the necessary cold hours (number of hours below to 7.2 °C). According to Tabuenca (1977), this requirement is highly cultivar-dependent, and it can range between 150 and 220 h for cultivars such as Desmayo Largueta, Marcona, or Nonpareil; between 220 and 350 h for varieties such as Ferraduel, Primorskii, Texas Drake, or Guara; or even up to 350 h for Cristo morto, Ferragnès or Yaltinski, and start to increase the temperatures at middle-end of winter. These processes are going to be directly affected by the stored reserves in the previous season during the end of Stage II and Stage III, just before the leaf-fall process. In this agreement, during pre-harvest and after this, the carbohydrates accumulation occurs, and ultimately, it will directly affect the yield potential in the following season (Esparza et al. 2001a), not only in terms of flowering potential but determining the fruit-setting and growing in the next season (Esparza et al. 2001b).

Considering this sharp differentiation in the almond phenological development, different authors have pointed out relevant results for regulated deficit irrigation

Table 19.1 Deficit irrigation studies concerning almond yield and its components

DI strategies defined	Main conclusions	References
Regulated-deficit irrigation during the kernel-filling stage); irrigated at 100% ET_C except for early June to early august at 20% ET_C	RDI did not promote significant reductions in kernel yield without effect on its size. Improvements on WUE with 30% less irrigation water respect to control trees were reached	Romero et al. (2004)
Four irrigation strategies were studied: 100% ET_C, 130% ET_C, 70% ET_C, and RDI irrigated at 100% ET_C with the exception during the kernel-filling period when was reduced at 20% ET_C	During the first two seasons, kernel dry-matter accumulation did not decrease with RDI; however, yield and kernel growth were reduced during the third and fourth seasons. Yield reductions for RDI were significant (20% respect to 100% ET_C), and water savings close to 60% of applied respect to 100% ET_C. RDI seemed to be more appropriate than 70% ET_C	Girona et al. (2005)
Three partial root-zone drying (PRD_{30}, PRD_{50}, and PRD_{70}) (reductions of ET_C at 30%, 50%, and 70%) treatments and RDI at 50% ET_C during the kernel-filling period were compared with a control of full irrigated trees at 100% ET_C	Except for PRD_{70}, the kernel weight was significantly reduced in remaining deficit irrigated treatments. Kernel yield, in % of the maximum yield at 100% ET_C, showed a linear decrease with decreasing water applied (slope of 0.43), which implies that a 1% water reduction lead implies 0.43% in yield. Water productivity increased with the reduction of water applied, reaching 123% in the case of PRD_{30}	Egea et al. (2010)
Four irrigation treatments on almond productivity: Control with fully irrigated at 100% ET_C, RDI irrigated as control trees with the exception during kernel-filling period receiving 40% ET_C, moderate and severe sustained deficit irrigation (SDI_m SDI_s) irrigated at 75–60% ET_C, and at 60–30% ET_C over the entire season, respectively.	The water stress imposed had not intensified the negative impact of deficit irrigation on final yield. Irrigation water productivity (IWP) increased with water stress. RDI and SDI_m showed similar responses. Therefore, the SDI_s appears to be the best option under severe water scarcity conditions	Egea et al. (2013)
The use of HYDRUS-2D model for drip-irrigated almond orchard, evaluating the daily fluctuations in water under: Full pulsed (FIp) with replacing of 100% ET_C, sustained deficit pulsed (SDIp) irrigated to replace 65% ET_C, and full continuous (FIc) irrigation with replacing of 100% ET_C	Water uptake efficiency under SDIp (68%) was higher respect to full water application of FIp and FIc (54–55%). The irrigation water productivity increased (37%), the yield was reduced by 8%, and 35% of irrigation water was saved with SDIp compared to FIp. Thus, SDIp appears to be a promising strategy, and irrigating almonds above the SDIp level may enhance unproductive water usage in the form of accelerated drainage	Phogat et al. (2013)
Six irrigation treatments: No irrigation (T_1), SDI irrigated at 25% ET_C (T_2) during the whole season,	Significant differences in nut yield and water use efficiency (WUE) among irrigation treatments were found. The	Mañas et al. (2014)

(continued)

Table 19.1 (continued)

DI strategies defined	Main conclusions	References
RDI irrigated at 50% ET_C with an exception during the kernel-filling period irrigated at 15% ET_C (T_3), SDI irrigated at 50% ET_C (T_4), RDI irrigated at 100% ET_C with the exception during the kernel-filling period irrigated at 20% ET_C (T_5), and a control of full irrigated trees at 100% ET_C for the entire irrigation season (T_6)	optimum yield response (1260 kg ha^{-1}) was from T_6 throughout the study period. Additionally, there were no significant differences in almond production and WUE between RDI and SDI strategies. The almond yield reductions for T_4 and T_5 respect to control T_6 were 23 and 31%, and the water savings of 50 and 55%, respectively	
Five irrigation treatments: Fully irrigated control at 100% ET_C, three RDI levels (55, 70, and 85% ET_C) applied for specific periods during the growing season, or SDI throughout the growing season, and a high irrigation level at 120% ET_C	Irrigation at 85% ET_C had no impact on kernel weight and yield, but 70% ET_C or 55% ET_C decreased kernel yield regardless of strategy, except for SDI 70%. During the last season, trees with SDI 70% ET_C produced higher kernel yield than those subjected under RDI at 70% ET_C. water stress tended to accelerate hull split in line with the deficit level.	Monks et al. (2017)
Four irrigation treatments were defined: a control that received the full pre-estimated ET_C, moderate SDI at 75% ET_C, moderate RDI irrigated as control, but only at 40% of control during the kernel-filling stage, and severe RDI irrigated as control trees and only 15% of control during the kernel-filling stage	The maximum average yield of 2508.4 kg ha^{-1} was obtained from control trees, while the three deficit irrigation strategies yielded 2150, 2040, and 1500 kg ha^{-1}, respectively. Although values varied, water productivity averaged 0.23 kg m^{-3} and did not differ among treatments	López-López et al. (2018b)
Three irrigation regimes were defined: Full-irrigation at 100% ET_C (FI), RDI_{50} irrigated at 50% ET_C during the kernel-filling stage, and low-frequency deficit irrigation (LFDI) subjected to continuous periods of irrigation-restriction defined by a threshold value of Ψ_{leaf} during the kernel-filling stage	Significant improvements for WUE were found, and no differences in nut yield between FI and LFDI, leading to important water savings (27 and 40%) can be achieved without compromising the almond productivity	García-Tejero et al. (2018b)
The response of three almond cultivars (Guara, Marta, and Lauranne) to different irrigation regimes: a full-irrigation at 100% ET_C (FI), over-irrigated treatment irrigated at 150% ET_C (150-ET_C), and RDI_{65} irrigated at 100% ET_C during the whole irrigation season, except during the kernel-filling period irrigated at 65% ET_C	Significant differences in physiological behaviour and yield responses among cultivars were found. Guara and Lauranne did not show significant improvements with 150-ET_C about FI and RDI_{65}, whereas cv. Marta recorded significant enhancements with 150-ET_C. thus, the cultivar is a determinant factor to take into consideration when deficit irrigation programmes are going to be applied in almond plantations	Gutiérrez-Gordillo et al. (2019b)

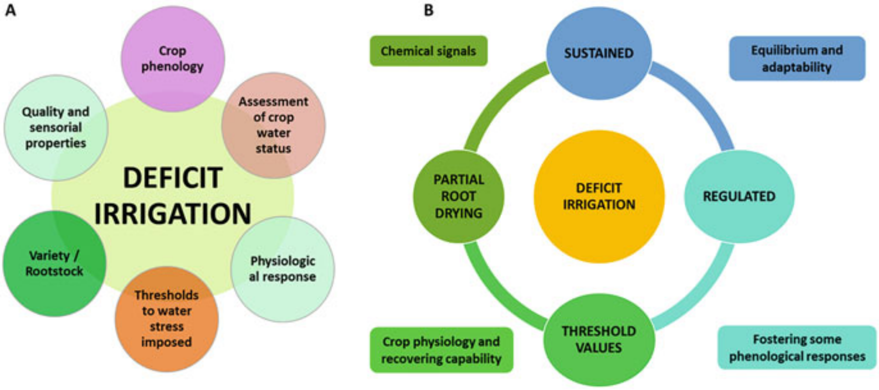


Fig. 19.4 Key factors under deficit irrigation (**a**) and different types of strategies with the main characteristic (**b**)

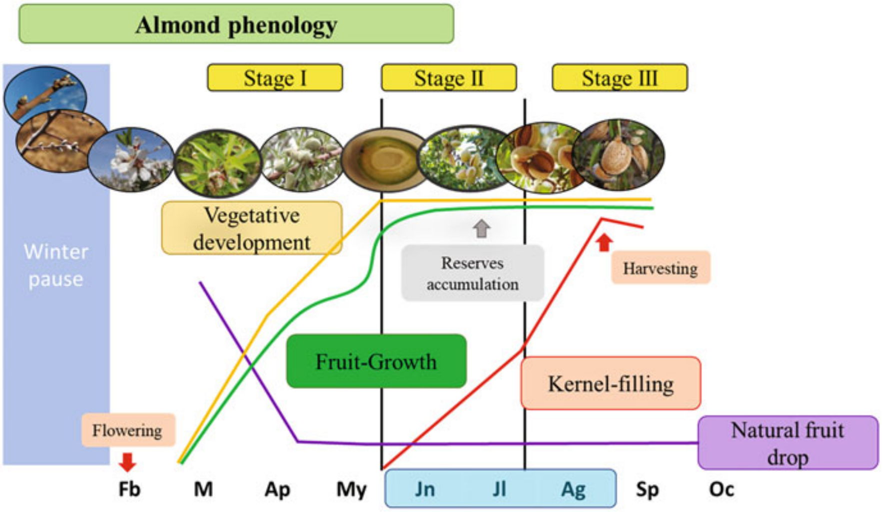


Fig. 19.5 Almond tree phenology throughout the nut production process

(RDI) strategies in which the water stress has been imposed at different phenological stages. Girona et al. (1993, 1997) and Micke (1996) concluded that water stress imposed during Stage I could promote fruits abortion, small fruits, and poor canopy development, which ultimately will affect the photosynthetic capacity. However, taking advantage of the climatic conditions registered in Mediterranean countries during this period, with a low evapotranspiration demand and a scarce canopy development during the first months, it would be very difficult to reach severe water stress situations. Something similar situation takes place when a water stress condition is imposed during Stage III. Although after harvesting, the crop water demand progressively comes down, if a drought condition takes place, significant adverse effects on yield can be registered for the following season. In this agreement, authors such as Micke (1996), Goldhamer and Viveros (2000), and Romero et al. (2004) reported adverse effects on bud differentiation and carbohydrates accumulation, these facts being reflected during the fruit-setting and vegetative development in the coming year.

Taking into account all these facts, after flowering, the presence of carbohydrates reserves is necessary to ensure proper shoots development together with the initial fruit growth, coinciding with a fast cell division process. However, the bloom is determined by the crop status during the previous year, insomuch as vegetative development is moving forward, the crop produces photo-assimilates, this being determinant for the following stages of fruit growth (Goldhamer and Girona 2012). Therefore, fruit size would be affected by the available resources during the first stage. In conclusion, if flowering and fruit set is directly influenced by the reserve's accumulation during the previous season (Esparza et al. 2001b), the fruit growth will be more dependent on the water and nutrients provided to the crop during the current season.

By contrast, several authors reported the exceptional capability of the almond crops to offer an excellent response to water stress when it is imposed during the kernel-filling period (phenological stage II). Goldhamer et al. (2006) or Romero et al. (2004) concluded the optimum response of almond to water withholding during this period. By contrast, Girona et al. (2005) observed yield losses when water withholding was applied during this period, mainly because of depletion in the dry mass accumulation. Lately, García-Tejero et al. (2018b) and Gutiérrez-Gordillo et al. (2019a) observed no significant difference in terms of kernel weight and final yield when a RDI treatment and a low-frequency DI treatment were applied during the kernel-filling period.

19.4.1 Selecting the Most Suitable DI Strategy Under Water Stress Conditions

Once the importance and advantages of almond phenological development to impose a proper DI strategy are defined, it is worthful summarizing some novelty results to implement a successful strategy under stress conditions.

Despite several defined DI strategies, Fig. 19.4 reflects the main strategies of DI and the advantages of each of them. On overall, water stress strategies imposed in almond can be defined in four different ways: sustained deficit irrigation (SDI) strategies, which are applied to achieve an equilibrium between canopy and fruit development; RDI strategies, which are focused on the sharp differentiation in the phenological development; the low-frequency deficit irrigation (LFDI) approaches, which are applied when the crop is subjected to irrigation-restriction cycles, keeping it within a range of stress; and the partial root drying (PRD) strategies, aimed to the chemical signals produced under water stress conditions, and responsible for the control of leaf stomata (García-Tejero et al. 2018a). Even though many DI strategies

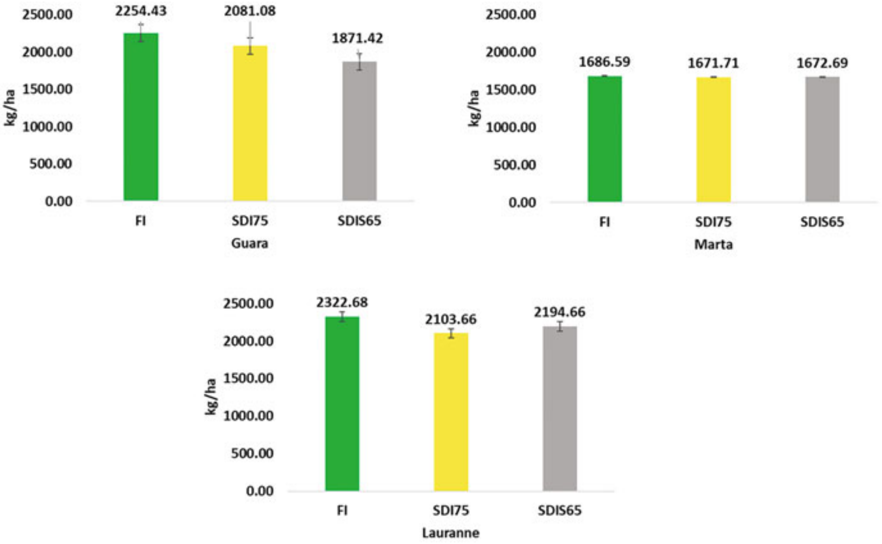


Fig. 19.6 Kernel yield in three young almond cultivars (*cvs.* Guara, Marta, and Lauranne) subjected to full irrigated conditions and two sustained deficit irrigation treatments (SDI_{75} and SDI_{65}), which received 75 and 65% of ET_C during the irrigation period

for almond trees have been developed, up today, there are no precise results in terms of yield when comparing SDI and RDI during kernel filling. Within this full of experiments, it is worth to remark some relevant results provided in the last few years under Mediterranean conditions. In this line, Goldhamer et al. (2006) concluded that under moderate water stress conditions, and with similar irrigation amounts, SDI offered lower yield reductions compared to RDI, and even more, being able to obtain similar productions to those registered under full irrigated (FI) conditions as reported by Girona et al. (2005). Similar results were outlined by Gutiérrez-Gordillo et al. (2019b), without yield reductions when an SDI strategy (at 75% of ET_C) had been applied. In this sense, comparable findings were recorded by authors of this chapter for three juvenile almond cultivars under semi-arid Mediterranean conditions (Fig. 19.6, not published data).

By contrast, Egea et al. (2013) or Alcón et al. (2013) not found differences between SDI and RDI strategies in terms of fruit yield through RDI trended to lower values than SDI. Moreover, Gutiérrez-Gordillo et al. (2019a) reported differences in terms of kernel yield in the same cultivars previously discussed in Fig. 19.6, in this case, when these almonds were subjected to full-irrigation and RDI treatments.

Significant findings were revealed by Gutiérrez-Gordillo et al. (2019c) and García-Tejero et al. (2018b) for mature almond trees (*cv.* Guara) in a long-term experiment. These authors applied three irrigation treatments: a FI treatment; and RDI during the kernel-filling period (50% of ET_C, RDI_{50}), and LFDI treatment

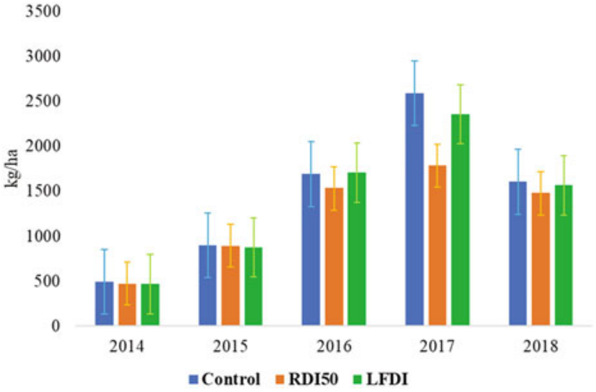


Fig. 19.7 Kernel yield in a long-term experience of almond trees (*cv.* Guara) subjected to full irrigated conditions (FI) and two deficit irrigation treatments: a regulated deficit irrigation strategy irrigated with 50% of ET_C during the kernel-filling period (RDI_{50}); and a LFDI treatment, subjected to irrigation-restriction cycles during the kernel-filling period, keeping the crop between leaf water potential (Ψ_{leaf}) values of those registered in the FI (during irrigation periods) and −2 MPa (Megapascal) during the restriction periods. More information about this methodology can be found at García-Tejero et al. (2018a)

(consecutive irrigation-restriction cycles during the same period of RDI_{50}) (Fig. 19.7). According to these findings, LFDI was able to obtain similar productions from those reported in FI during the studied years. Moreover, this treatment was liable for improving the yields registered in RDI_{50}, where this strategy offered significantly worse results under FI.

Relating to PRD strategies, Egea et al. (2009, 2011) concluded that a PRD strategy that at the end of the irrigation period had received 50% ET_C, was able to obtain similar productions to those with an RDI strategy that on overall, had been received 20% more water than the previous one. More relevant results were obtained in a PRD strategy in which water withholdings close to 70% were imposed. This treatment offered similar yields to those obtained in the RDI_{70} previously discussed, without significant effects in terms of water potential and gas exchange parameters. These absences of differences suggest that PRD strategy did not show a relevant chemical signal from (abscisic acid synthesis) able to reduce the stomatal conductance (gs) rates and maintain the leaf water potential values.

Between the affected parameters by DI strategies on almond trees, not only the final yield was modified, but also some morphological parameters (kernel size), the ratio shell/kernel, and irrigation water productivity. In this sense, Fig. 19.8 reflects the unit weight of kernel, in the same three almond cultivars and irrigation strategies presented in Fig. 19.6.

According to these results, the most relevant is the absence of effects in terms of almond nut size in case of *cvs*. Marta and Lauranne. However, *cv*. Guara increased in almond nut size in the SDI_{65} treatment. These results together with those obtained in terms of final yield would evidence effects of water stress on fruit-setting (fewer

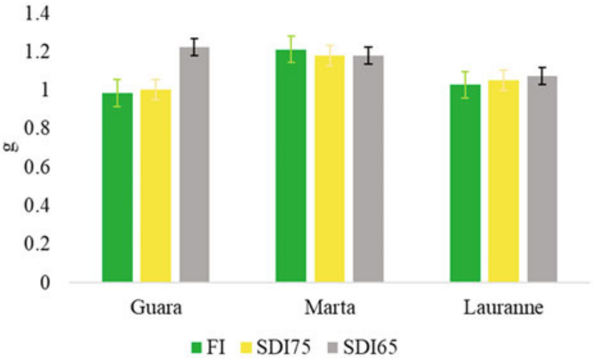


Fig. 19.8 Kernel weight in three young almond cultivars (*cvs.* Guara, Marta, and Lauranne) subjected to full irrigated conditions (FI) and two sustained deficit irrigation treatments (SDI_{75} and SDI_{65}), which received 75 and 65% of ET_C during the irrigation period

fruits in SDI_{65}), although this negative point was balanced with a larger kernel size, which could be assumed as a positive quality point in terms of the final value of almonds. Similar results were reported by Gutiérrez-Gordillo et al. (2019a) for RDI strategies, this being a positive aspect of being taken into account. Thus, it could be concluded that the reductions in terms of almond yield do not exclusively depend on DI strategy used but also the crop physiological response to the water stress situations.

19.5 The Importance of Crop Water Status Assessment When Deficit Irrigation is Being Imposed: The Leaf as the Plant Mirror

When a DI is imposed, the first evidence in terms of crop physiological response can be monitored at leaf level by different measurements that help us to understand what is happening into the crop. Agronomical response (total yield and its related components) is directly determined by reductions in terms of the photosynthetic rate (A_N). Studying and discussing the whole mechanism involved in carbon assimilation would require much information and time, and for this reason, we are going to focus the effort in explaining those main changes occurred in almond trees when water stress is applied; especially in those physiological variables susceptible of being monitored. In this agreement, according to Hsiao (1990) when plants are subjected to water stress, the first evidence are reflected in g_s reductions, this being a defensive response to reduce the water losses throughout stomata. Subsequently, this reduction in carbon assimilation could be accompanied by other biochemical limitations at Rubisco level and electron transport chain (Flexas et al. 2009; Egea et al. 2011). This apparent relationship between water stress and A_N reduction does not occur in the same way for the different vegetable species (Flexas et al. 2018). In this context, after different research experiences, the resistance of almond to water stress is relatively high, comparing to other woody Mediterranean crops as olives (Hernandez-Santana et al. 2016). Thus, almond could be considered as an anisohydric crop, because of its g_s limitation under drought conditions is very limited (Egea et al. 2011; Xiaoli and Frederick 2018; García-Tejero et al. 2018b). In this line, Romero et al. (2004) observed that g_s reductions close to 50% from its maximum rate would be accompanied by A_N depletion around 30%. Focusing these results with those obtained by García-Tejero et al. (2018b), it could be assumed that, descends around 50% in terms of Ψ_{leaf}, would promote depletion of carbon assimilation rate close to 15–20%, evidencing the high almond capability to keep maximum g_s values (~0.3 mol H_2O m^{-2} s^{-1}) even when Ψ_{leaf} values are close to −2.5 MPa (Hernandez-Santana et al. 2016). According to these findings, almond would be able to keep optimum rates of g_s, $A_{N,}$ and hence increasing the WUE_i (Rouhi et al. 2007). By contrast, this down-regulation of g_s can be accompanied by a leaf senescence when drought conditions are very severe and supported during a long-term period (Spinelli et al. 2016). By considering these physiological characteristics, it is determinant to define the most appropriate parameter to assess the crop physiological status, especially when DI strategies are being imposed to avoid significant effects on vegetative development, yield, and fruit quality.

19.5.1 Monitoring Almond Water Status for a Proper Irrigation Scheduling Under Water Scarcity Scenarios: The Particular Case of Canopy Temperature

As previously discussed, crop water monitoring has great importance when this is subjected to water stressed situations. In this agreement, there is a keen interest focused on developing robust tools able to monitor the plant-water status, implementing these technologies on agricultural systems, allowing not only proper crop management but also defining the most advisable irrigation scheduling strategies. For an in-depth knowledge of crop physiological responses, useful tools to crop water monitoring under drought conditions are required (Padilla-Díaz et al. 2016; Meena et al. 2020a). Many works have been published to establish the most suitable device, analysing the main advantages and disadvantages for each of them [Shackel 2011 for the case of water potential; Rodríguez-Domínguez et al. (2016) for g_s; Zimmermann et al. (2008) for the instance of leaf turgor probes; and Griñán et al. (2017) for sap flow measurements and trunk diameters fluctuations]. Furthermore, thermal imaging has been widely studied to monitor the crop water status (Costa et al. 2013a), underlining for being a non-destructive, rapid, and non-invasive methodology that allows work at different scales (from seedlings to woody crops and large crop areas). This technique offers quantitative information about the crop water status and shows quantitative as qualitative differences between non-water stressed and water stressed almond trees (Fig. 19.9).

The basis for how this tool works is related to the evaporative cooling process associated with the crop E rate. Thus, when a crop is being cultivated under full-irrigation conditions, water movement from soil to the atmosphere is directly dependent on the atmosphere vapour pressure deficit, going out as vapour through stomata. By contrast, when a water withholding is imposed, a depletion in terms of E is observed, decreasing the water loss from the stomata and hence the crop water

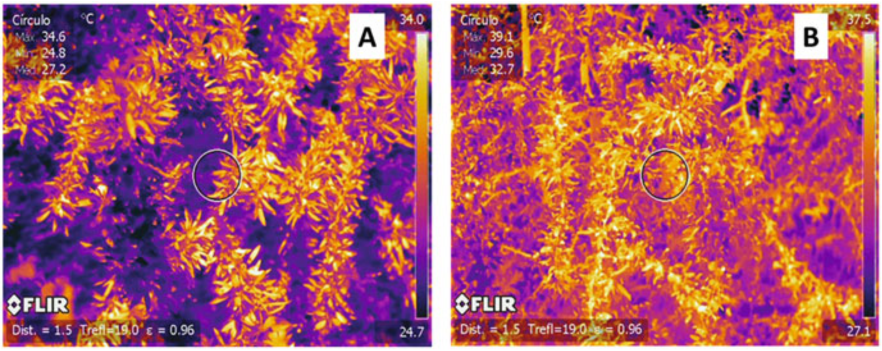


Fig. 19.9 Thermal imaging of almond canopies under non-water stress (**a**) and water stress conditions (**b**)

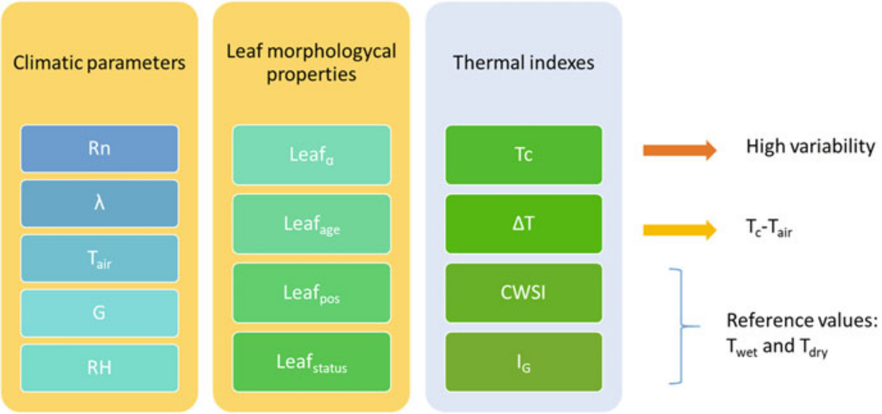


Fig. 19.10 Climatic parameters and leaf morphological properties involved on the total value of canopy temperature (T_C); and the thermal indexes

extraction. Associated with this descend in E, the leaf evaporative cooling is reduced, increasing canopy temperature T_C, this response is directly related to crop response to water stress (Jones et al. 2009; Costa et al. 2013b; Pou et al. 2014).

However, T_C is not exclusively dependent on water availability but other vital variables that can significantly influence their absolute values (Fig. 19.10).

According to Costa et al. (2013a), climatic and morphological parameters are going to determine the value of T_C, and hence, these effects should be taken into account when thermal imaging is going to be applied to assess the crop water status. Climatic parameters such as air temperature, radiation, relative humidity, or wind and leaf morphological properties will determine the absolute value of the leaf (or canopy) temperature. Different thermal indexes have been proposed to normalize the absolute values of T_C and consequently to minimize the effects of these

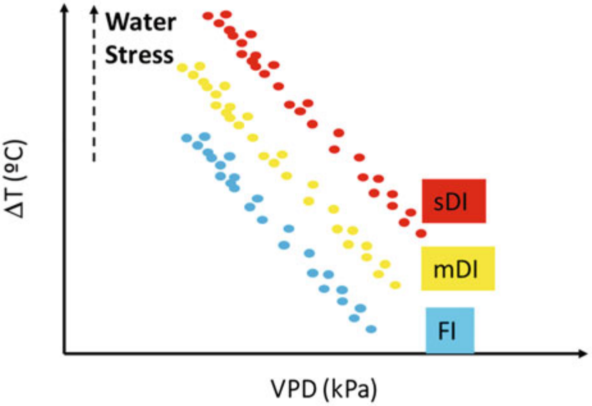
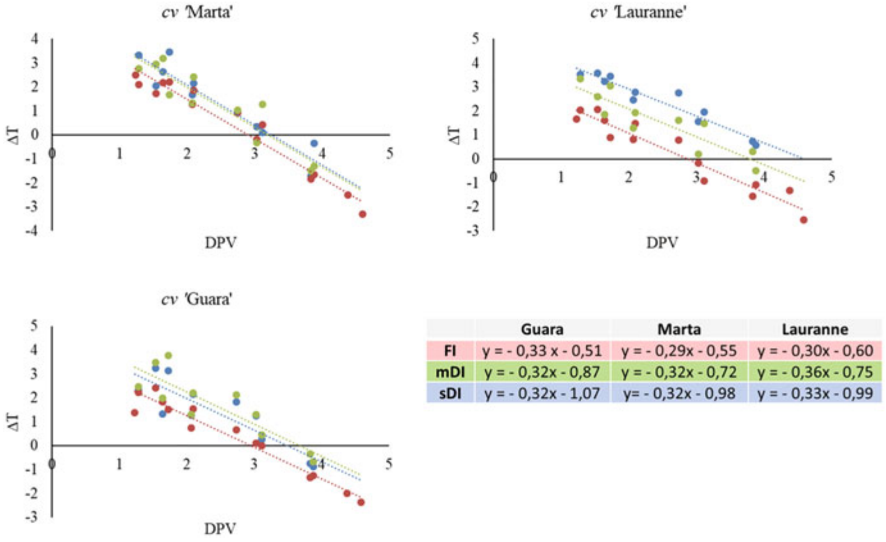


Fig. 19.11 Non-water stress baselines (blue points, for full-irrigation (FI) conditions and water stress baselines for two different situations: a moderate deficit irrigation treatment (yellow spots, mDI) and severe deficit irrigation treatment (red spots, sDI). ΔT, the thermal index that represents the difference between a canopy and air temperature; VPD, vapour pressure deficit

parameters. Between these indexes, the crop water stress index (CWSI) as the relative index to stomatal conductance (I_G) requires to implement some reference values such as T_{wet} (the absolute value that would reflect the Tc value when the crop is full irrigated and hence E_{level} is maximum) or T_{dry} (the absolute value that would simulate the T_C value when stomata are closed). Despite the fact that these indexes provide excellent information, they require artificial reference values, and many times this difficult its usage. Regarding the same, Idso et al. (1981) pointed out the substantial positive differences between a canopy and air temperature (ΔT) when water stress is imposed; meanwhile, these differences are much more stable and negative under full-irrigation conditions. According to García-Tejero et al. (2018c), a proper strategy for interpreting the thermal information provided by ΔT index is by defining the non-water-stressed baselines (NWSBs); linear functions that relate ΔT values when a crop is transpiring under non-limiting conditions, with vapour pressure deficit (VPD) values simultaneously obtained when ΔT is measured. Thus, this NWSB allows us to know the optimum value of ΔT for specific climatic conditions defined in terms of the VPD (Fig. 19.11).

As well as NWSBs can be identified, it is possible to establish the water-stress baselines (WSB*)* when water withholdings (defined in terms of ET_C) are imposed (García-Tejero et al. 2018c) (Fig. 19.11). This possibility would enhance irrigation scheduling, mainly when DI strategies are being applied (Egea et al. 2017). These WSBs could be defined as a known DI strategy, which would be associated with potential water savings and yield losses. According to this, García-Tejero et al. (2018c) defined these NWSBs and WSBs for three almond cultivars (*cvs.* Guara, Lauranne, and Marta) subjected to three different irrigation strategies. These authors concluded that for each cultivar, no differences among treatments in the slope functions were found, contrasting with the interception point (Fig. 19.12).

Taking into account these relationships and the absence of significant yield losses in the studied cultivars, the functions corresponding to moderate or severe DI strategies could be used for irrigation scheduling and taking decisions when water



	Guara	Marta	Lauranne
FI	y = - 0,33 x - 0,51	y = - 0,29x - 0,55	y = - 0,30x - 0,60
mDI	y = - 0,32x - 0,87	y = - 0,32x - 0,72	y = - 0,36x - 0,75
sDI	y = - 0,32x - 1,07	y= - 0,32x - 0,98	y = - 0,33x - 0,99

Fig. 19.12 Experimental results of non-water stress baselines (FI) and water stress baselines for two different situations: a moderate deficit irrigation treatment (mDI) and severe deficit irrigation treatment (sDI). ΔT, the thermal index that represents the difference between a canopy and air temperature; VPD, vapour pressure deficit (Data from García-Tejero et al. 2018c)

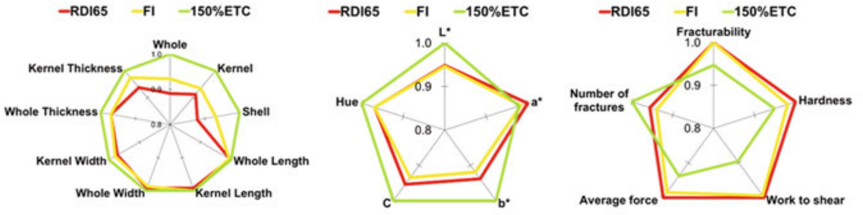
requirements are up to the water availability, ensuring suitable productions and water savings close to 3500 m^3 ha^{-1}.

In short, thermal data was a precise indicator of the almond water status, concretely, the index ΔT that allow establishing the NWSBs and WSBs, being these functions were an accurate tool for irrigation scheduling for different cultivars.

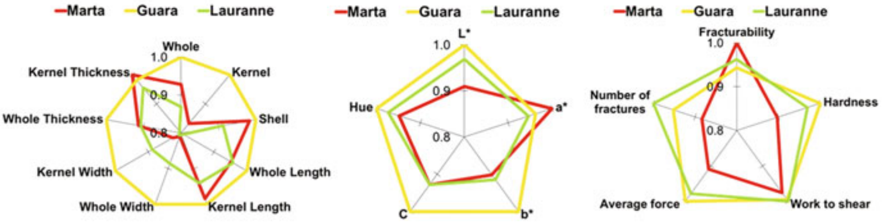
19.6 Improving the Competitiveness of Almond Production Under Drought Conditions: Deficit Irrigation and Fruit Quality

The essential role of water in plants is boundless, starting with being reactant, medium for the ionization of the metabolites or stabilization of biomembranes, and ending with keeping the structure rigidity. Several studies reported the possibility to irrigate under the crop requirements, preserving the almond quality, and for some parameters (morphological, mineral content, organic acids and sugars, or the fatty acid profile), even improving them with no or slightly reduction of yield.

According to the morphological parameters, fruit weight, size, colour, and texture are the most relevant parameters that could be modified when a DI strategy is imposed, being possible to find different responses in terms of the cultivar. In this regard, it is worth mentioning the most relevant results obtained by Lipan et al. (2019a) in three commercial cultivars of almond irrigated under three different



Size and weight by irrigation treatment Color by irrigation treatment Texture by irrigation treatment



Size and weight by cultivar Color by cultivar Texture by cultivar

Fig. 19.13 Morphology, instrumental colour, and instrumental texture in three different almond cultivars (*cvs.* Guara, Marta, and Lauranne) subjected to different irrigation treatments: FI, irrigated at 100% ET_C; 150% ET_C, irrigated at 150% of ET_C; and RDI_{65}, irrigated at 65% of ET_C during the kernel-filling period

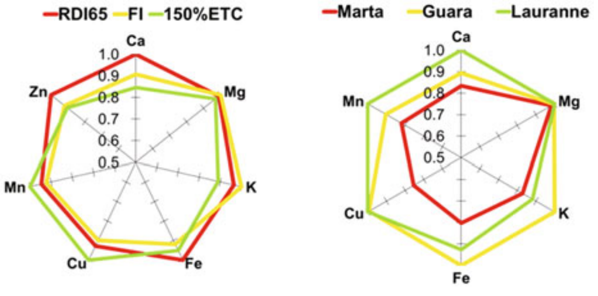
strategies: a control treatment (FI) which was fully irrigated applying 100% of ET_C, an over-irrigated treatment (150% ET_C), which was irrigated with doses close to 150% ET_C, and RDI_{65} treatment, which was irrigated receiving the same water amounts of FI treatment, except during the kernel-filling period, when it was irrigated according to 65% of ET_C.

The irrigation dose and cultivar effects on the morphological parameters are shown in Fig. 19.13. The analysed parameters were weight, size, colour, and texture. Texture parameter included fracturability, hardness, work done to shear, average force, and quantity of fractures. Almond fracturability shows the sample brittleness, while the maximum force represents almond hardness on the graph, and it is correlated with the force needed to bite the almond between the molars. Work to shear expresses the work done up to the maximum peak force. This area represents the energy required to overcome the strength of the internal bonds within the almonds. The average force is a function which helps to calculate the data average from the curve between the two selected anchors, and finally, the quantity of fractures determines the almond crunchiness.

The morphological parameters showed significant changes as response to irrigation treatment and cultivar (Fig. 19.13). Regarding irrigation dose factor, almonds over irrigated showed the highest almonds in terms of kernel weight, colour lightness (L^*), and coordinate b^*, while lowest values of a^* coordinates and texture were observed. In other words, when the almonds received irrigation water above the optimum, softer and lighter almonds with less red and more yellow notes were observed. Moreover, almond texture was affected with the moisture of the sample, the higher the moisture content, the softer the almond texture. The cultivar is also an essential factor when establishing the most suitable irrigation strategy to be applied. For instance, *cv*. Guara generated almonds with higher values of weight, size, colour, and hardness. More recently, it has been concluded that the consumer acceptability depends on the texture parameter (Lipan et al. 2019b); and for this reason, harder almonds such as Guara (76 Newtons) and Lauranne (74 Newtons) might be more accepted by the consumers. Overall it can be concluded that not only irrigation dose but also the cultivar significantly affects the morphological parameters of almonds. For instance, RDI_{65} produced hard and fracturable almonds with darker skin ($L^* = 49$), while higher hardness characterized cultivars such as Guara and Lauranne work to shear and average force values. Also, *cv*. Guara almonds presented the lighter skin and *cv*. Marta the darkest one, and the latter also showed intense red skin ($a^* = 18.7$).

The mineral content of the almond kernel is accumulated by the plant both from the soil and the irrigation water applied during the growing cycle (Yada et al. 2011). Consequently, many factors, such as environmental and agronomical practices (geographical location, cultivar, water source, irrigation system, fertilizers, etc.) can affect the mineral content of the plant tissue. Thus, studying the mineral content of plants under controlled water stress conditions is of utmost interest from a quality point of view. Mineral content can be either expressed in general as the total inorganic residue obtained after the plant tissue incineration (ash) or as an individual element. Elements such as calcium (Ca), copper (Cu), iron (Fe), magnesium (Mg), potassium (K), phosphorus (P), selenium (Se), sodium (Na), manganese (Mn), and zinc (Zn) are the most relative minerals in almonds (Yada et al. 2011). Almond kernels contain approximately 3.3 g 100 g^{-1} of ash for the almonds grown in Spain (Lipan et al. 2019a), 3.4 g 100 g^{-1} from Lebanese, 3.8 g 100 g^{-1} from Turkey, and 2.4–4.6 g 100 g^{-1} from California (Yada et al. 2011). Regarding the individual elements, authors working with *cv*. Vairo under DI conditions reported a significant effect of the irrigation dose on the contents of Ca, K, and Mn. The K content increased when a moderate RDI was applied to the control (7.7 g kg^{-1}) (Lipan et al. (2019b). However, the stress intensity must be controlled due to the impact that can have on the fruit quality. Figure 19.14 displays the mineral content as affected by irrigation treatment and cultivar. As observed in this study, K, Ca, or Zn contents increased with the water-stress imposed. In relation to the cultivar effect, relevant differences were observed. The highest values of Ca and Mn were observed in Lauranne, whereas Guara obtained the highest values of K, Fe, and Cu. By contrast, Ca levels for *cvs*. Marta, Guara, and Lauranne were higher than those reported for *cv*. Vairo by Lipan et al. (2019b).

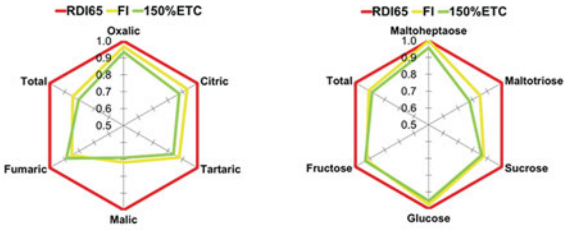
Carbonell-Barrachina et al. (2015) highlighted higher levels of Zn and Ca for pistachios cultivated under DI strategies. In contrast, Alimohammadi et al. (2012) did not report differences in the mineral content of almonds cultivated under DI, as well as Nakajima et al. (2004) working with other different crops (grapes, olive, or apple). Even more interesting are the effects promoted by irrigation treatments on the content of sugars and organic acids. Figure 19.15 represents the impact of irrigation



Minerals by irrigation treatment

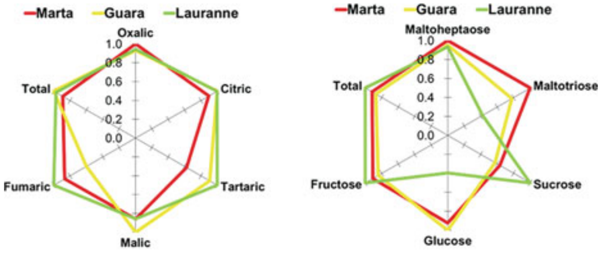
Minerals by cultivar

Fig. 19.14 Mineral content in three different almond cultivars (*cvs.* Guara, Marta, and Lauranne) subjected to different irrigation treatments: FI, irrigated at 100% ET_C; $150\%ET_C$, irrigated at 150% of ET_C; and RDI_{65}, irrigated at 65% of ET_C during the kernel-filling period



Organic acids by irrigation treatment

Sugars by irrigation treatment



Organic acids by cultivar

Sugars by cultivar

Fig. 19.15 Organic acids and sugar content in three different almond cultivars (*cvs.* Guara, Marta, and Lauranne) subjected to different irrigation treatments: FI, irrigated at 100% of ET_C; $150\%ET_C$, irrigated at 150% of ET_C; and RDI_{65}, irrigated at 65% of ET_C during the kernel-filling period

and cultivar on these parameters. Almonds cultivated under RDI_{65} conditions showed higher levels of both organic acids and sugars, while among cultivars, Lauranne registered the highest levels of sugars and organic acids. Similarly, *cv.* Guara had a higher content of organic acids but with the lowest sugar content. All cultivars were affected by water stress both in organic acids and sugars. The results of other authors are divided in “strong relationship” (Lipan et al. 2019b) and “no relationship” (Sánchez-Bel et al. 2008; Egea et al. 2009) between water stress and total organic acids content. What is clear is that the water stress enhances sugars and so sweetness by increasing the glucose content due to the osmotic adjustment (Yakushiji et al. 1996). This phenomenon can be activated by the accumulation of solutes abundant in hydroxyl groups such as sugars, in the fruit cytoplasm and act as a mechanism for coping with water shortage (Ripoll et al. 2014).

Finally, the most relevant results were observed about the lipid and fatty acids fraction. Lipids are present as intracellular oil droplets in the cotyledon tissue of the

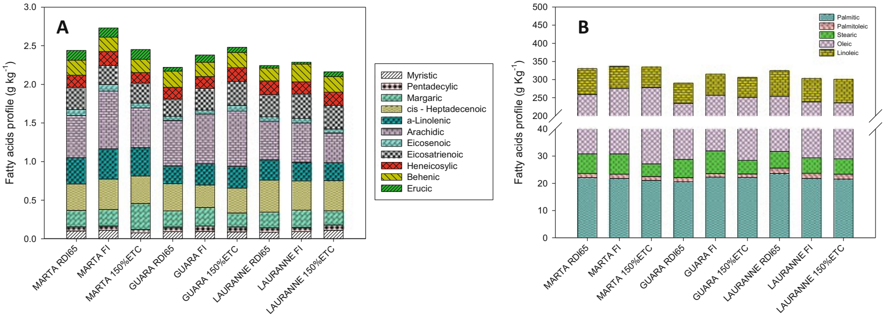


Fig. 19.16 Profile of minority (A) and majority fatty acids (B) in three different almond cultivars (*cvs.* Guara, Marta, and Lauranne) subjected to different irrigation treatments: FI, irrigated at 100% of ET_C; 150%ET_C, irrigated at 150% of ET_C; and RDI_{65}, irrigated at 65% of ET_C during the kernel-filling period

seed (Young et al. 2004; Grundy et al. 2016). Almond lipid content ranged between 35 and 67%, and the one cultivated in Spain showed values between 40 and 67% (Mandalari et al. 2010; Yada et al. 2011). Almonds, as well as other nuts, are a good source of lipids and so a good caloric source without increasing the cholesterol level in humans due to its composition mainly composed by mono (MUFA) and polyunsaturated fatty acids (PUFA) (Lipan et al. 2019a). Studies suggest that lipid content and profile fraction are not only genotype-dependent but also might be influenced by other factors such as climatic conditions, season, harvest year, or any interaction of these factors (Yada et al. 2011).

For this reason, it is of utmost importance defining the irrigation strategy and amount in each cultivar, to assure optimal productivity with little impact on fruit quality. In this context, Fig. 19.16 shows the almond's lipid profile for three varieties and three irrigation treatments. Considering the effect of the irrigation; myristic, palmitoleic, *cis*-heptadecenoic, oleic, linoleic, α-linolenic, arachidic, eicosenoic, and erucic acid were significantly affected by the irrigation dose. Moreover, saturated fatty acids (SFAs) were significantly higher in FI than RDI_{65}, while palmitoleic (MUFAs), *cis*-heptadecenoic (MUFAs), and linoleic (PUFAs) were significantly higher in RDI_{65}. Moreover, as said before, the cultivar was an essential factor when characterizes the lipid fraction. For instance, Marta registered higher contents of myristic, *cis*-heptadecenoic, oleic, α-linolenic, arachidic, eicosenoic, and erucic. Guara showed the highest content of arachidic acid, whereas Lauranne evidenced the most top content of palmitoleic and linoleic acids.

As shown in Fig. 19.17, RDI_{65} samples presented lower oleic: linoleic ratio and MUFAs content and a higher content of PUFAs. It means almonds were more susceptible to oil oxidation because of high oleic: linoleic ratio means fewer MUFAs (oleic acid) and this compound is linked to high oil stability (Kodad et al. 2014). Nevertheless, regarding the health properties, linoleic acid is a PUFA (omega 6) essential for the human body with a vital role in the death of cardiac cells, among other facts (EFSA 2009). The human body is not able to synthesize this fatty acid,

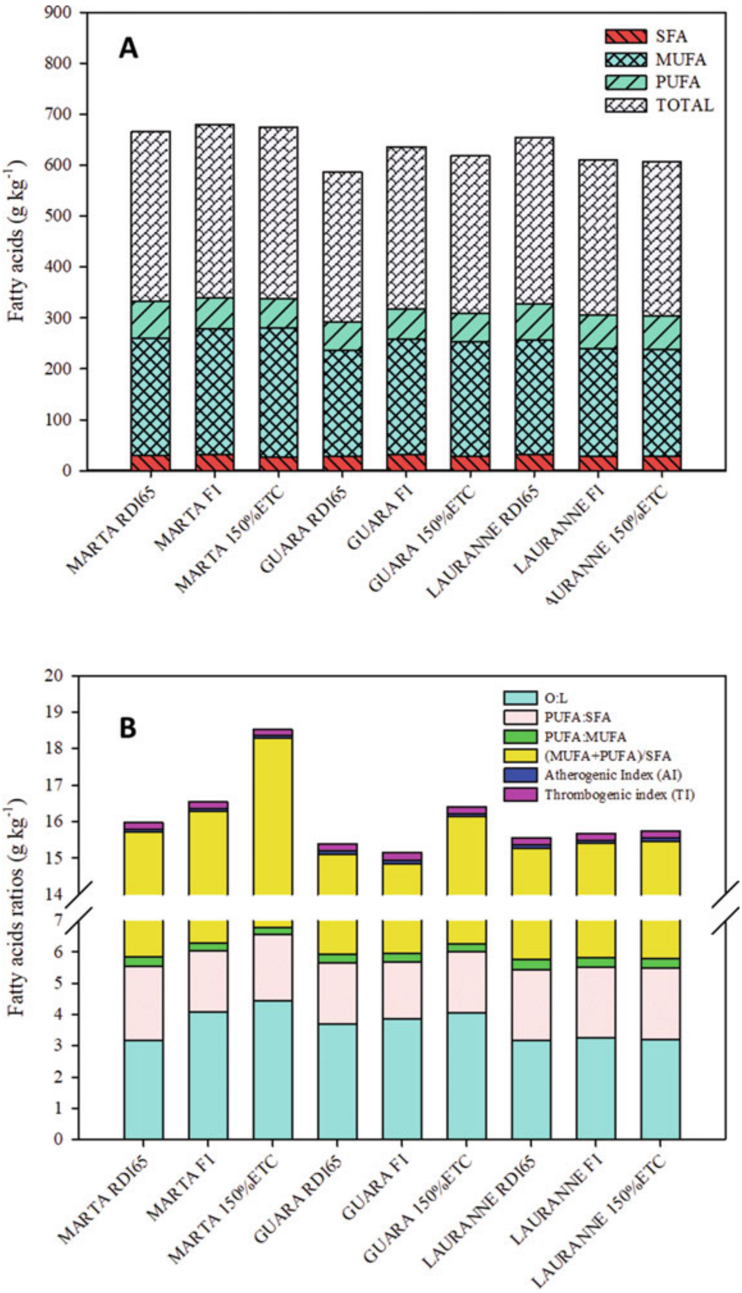


Fig. 19.17 Total fatty acids classification (**a**) and their relationships (**b**) in three different almond cultivars (*cvs.* Guara, Marta, and Lauranne) subjected to different irrigation treatments: FI, irrigated at 100% of ET_C; 150%ET_C, irrigated at 150% of ET_C; and RDI_{65}, irrigated at 65% of ET_C during the kernel-filling period

and it is necessary for biological processes and to preserve metabolic integrity. The European Food Safety Authority recommends 10 g day^{-1} of linoleic acid as the reference intake value (EFSA 2009); thus, the consumption of 50 g of RDI$_{65}$ almonds will help to assure approximately 33% of the linoleic acid daily intake recommended by Food Safety Authority. Regarding the cultivar, high content of MUFAs was observed for Marta, while significantly high content of PUFAs was shown for *cv*. Lauranne. An increase in PUFAs was also reported by other authors working with different crops such as pistachios and olives (Cano-Lamadrid et al. 2015; Carbonell-Barrachina et al. 2015; Sánchez-Rodríguez et al. 2019).

19.7 Conclusions

Seeking a balance between competitiveness and sustainable agriculture requires many efforts, especially under the current scenarios of climate change and water scarcity. Three questions should be considered to achieve a successful strategy. The first one, selecting appropriate crops with high consumer demand, and with proper marketable acceptability. In this regard, the almond crop would represent an excellent alternative to other irrigated crops in Mediterranean areas, where the climate change effects and water deficit are progressively increasing; mainly, because of the large market space in Europe and other emerging countries for almonds production.

Secondly, selected crops should have a well-known capability to be developed under water scarcity scenarios. In this agreement, according to the results offered in the present work, and the physiological response of almond to drought conditions, there is sufficient evidence to affirm that, this crop has a high capability of obtaining exciting productions, with significant water savings, minimizing the yield losses, and increasing the irrigation water productivity. Even more, up today, there are a broad set of tools that can help technicians and producers to develop appropriate taking decisions when a DI strategy is used. Among them, thermography would be a suitable technique, offering different ways of establishing the physiological threshold values and the proceedings for the assessment of almond water status.

And finally, as the third and crucial question would be related to the capability of improving the fruit quality and hence increase the final added value of almond. In this context, the novelty results discussed in the present chapter evidence the benefits in the chemical and sensory profile of almonds (especially in terms of healthy compounds) cultivated under moderate water stress conditions. These improvements obviously would help to equilibrate the possible economic losses (because of yield reductions), offering a better product to the fruit quality and consumer acceptance.

19.8 Future Perspectives

Despite quite advances have been done to define suitable DI strategies for almond, it is vital to delve into the knowledge respect to water management under more severe water scarcity situations. The almond cultivation and its adaptation to future climate change scenarios is undoubtedly one of the greatest challenges. Developing new tolerant varieties with a higher added value in relation to the nutrient profile will reinforce the market value of almonds cultivated under water withholdings. To ensure the enhancement of this product, developing quality seals with international credibility will help to certify the almond products that have been obtained under sustainable strategies, environmentally friendly and with substantial improvements in relation to healthy foods.

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References

Albrigo LG, Saúco VG (2004) Flower bud induction, flowering and fruitset of some tropical and subtropical fruit tree crops with special reference to citrus. Acta Hortic 632:81–90. https://doi.org/10.17660/ActaHortic.2004.632.10

Alcón F, Egea G, Nortes PA (2013) Financial feasibility of implementing regulated and sustained deficit irrigation in almond orchards. Irrig Sci 31:931–941. https://doi.org/10.1007/s00271-012-0369-6

Alimohammadi R, Mousavi A, Tatari M, Fattahi A (2012) Effects of deficit irrigation during different phenological stages of fruit growth and development on mineral elements and almond yield. Iran J Water Res Agric 26:143–159

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. FAO Irrigation and Drainage paper (56). FAO, Rome

Arquero O (2013) Water use by drip-irrigated late-season peaches. Irrig Sci 22:187–194. https://doi.org/10.1007/s00271-003-0084-4

Ayars JE, Johnson RS, Phene CJ, Trout TJ, Clark DA, Mead RM (2003) Manual del almendro. Consejería de Agricultura, Pesca y Desarrollo Rural, Junta de Andalucia, Sevilla

Bindi M, Olesen JE (2011) The responses of agriculture in Europe to climate change. Reg Env Change 11:151–158. https://doi.org/10.1007/s10113-010-0173-x

Cano-Lamadrid M, Girón IF, Pleite R, Burló F, Corell M, Moriana A, Carbonell-Barrachina AA (2015) Quality attributes of table olives as affected by regulated deficit irrigation. LWT - Food Sci Technol 62:19–26. https://doi.org/10.1016/j.lwt.2014.12.063

CAPDR (2016) Caracterización del sector de la almendra en Andalucía. Secretaría General de Agricultura y Alimentación, Consejería de Agricultura, Pesca y Desarrollo Rural. Junta de Andalucía. 34 pp. Available from: http://www.juntadeandalucia.es/agriculturaypesca/observatorio/servlet/FrontController?action=RecordContent&table=12030&element=1654785

Carbonell-Barrachina AA, Memmi H, Noguera-Artiaga L, Gijon-Lopez MD, Ciapa R, Perez-Lopez D (2015) Quality attributes of pistachio nuts as affected by rootstock and deficit irrigation. J Sci Food Agric 95:2866–2873. https://doi.org/10.1002/jsfa.7027

Costa JM, Grant O, Chaves MM (2013a) Thermography to explore plant-environment interactions. J Exp Bot 64:3937–3949. https://doi.org/10.1093/jxb/ert029

Costa JM, García-Tejero IF, Chaves MM (2013b) O uso da termografia na agricultura moderna. APH 113:30–34

De Ollas C, Morillón R, Fotopoulos V, Puértolas J, Ollitrault P, Gómez-Cadenas A, Arbona V (2019) Facing climate change: biotechnology of iconic Mediterranean woody crops. Front Plant Sci 427:1–23. https://doi.org/10.3389/fpls.2019.00427

Doll D (2009) The seasonal patterns of almond production. University of California Cooperative Extension. Available at: http://thealmonddoctor.com/2009/06/22/the-seasonal-patterns-of-almond-production/

Doorenbos J, Pruitt WO (1977) Crop water requirements. Irrig Drain. Paper 24, FAO, Rome

EC (2018) Agri-food trade in 2017. Another record year for EU agri-food trade DG AGRI briefing No MAP 2018–2011

EEA (2017) European Environment Agency Report. Climate change, impacts and vulnerability in Europe. An indicator-based report. 424 pp

EEA (2019) Climate change adaptation in the agriculture sector in Europe EEA Report 4/2019. 112 pp. ISBN 9789294800725

EFSA (2009) Labelling reference intake values for n-3 and n-6 polyunsaturated fatty acids. Scientific opinion of the panel on dietetic products, nutrition and allergies on a request from the commission related to labelling reference intake values for n-3 and n-6 polyunsaturated fatty acids. EFSA J 1176:1–11. https://doi.org/10.2903/j.efsa.2009.1176

Egea G, González-Real MM, Baille A, Nortes PA, Sánchez-Bel P, Domingo R (2009) The effects of contrasted deficit irrigation strategies on the fruit growth and kernel quality of mature almond trees. Agric Water Manag 96:1605–1614. https://doi.org/10.1016/j.agwat.2009.06.017

Egea G, Nortes PA, Gonzalez-Real MM, Baille A, Domingo R (2010) Agronomic response and water productivity of almond trees under contrasted deficit irrigation regimes. Agric. Water Manag 97:171–181. https://doi.org/10.1016/j.agwat.2009.09.006

Egea G, González-Real MM, Baille A, Nortes P, Díaz-Espejo A (2011) Disentangling the contributions of ontogeny and water stress to photosynthetic limitations in almond trees. Plant Cell Environ 34:962–979. https://doi.org/10.1111/j.1365-3040.2011.02297.x

Egea G, Nortes PA, Domingo R, Baille A, Pérez-Pastor A, Gónzalez-Real MM (2013) Almond agronomic response to long term deficit irrigation applied since orchard establishment. Irrig Sci 31:445–454. https://doi.org/10.1007/s00271-012-0322-8

Egea G, Padilla-Díaz CM, Martinez-Guanter J, Fernández JE, Pérez-Ruiz M (2017) Assessing a crop water stress index derived from aerial thermal imaging and infrared thermometry in super-high-density olive orchards. Agric Water Manag 187:210–221. https://doi.org/10.1016/j.agwat.2017.03.030

Espadafor M, Orgaz F, Testi L, Lorite IJ, Villalobos FJ (2015) Transpiration of young almond trees in relation to intercepted radiation. Irrig Sci 33:265–275. https://doi.org/10.1007/s00271-015-0464-6

Esparza G, DeJong TM, Weinbaum SA, Klein I (2001a) Effects of irrigation deprivation during harvest period on yield determinants in mature almond trees. Tree Physiol 21:1073–1079. https://doi.org/10.1093/treephys/21.14.1073

Esparza G, DeJong TM, Weinbaum SA (2001b) Effects of irrigation deprivation during the harvest period on nonstructural carbohydrate and nitrogen contents of dormant, mature almond trees. Tree Physiol 21:1081–1086. https://doi.org/10.1093/treephys/21.14.1081

FAOSTAT (2018) Food and Agriculture Organisation of the United Nations. Available at: http://www.fao.org/faostat/en/#data/QC

Fereres E, Martinich DA, Aldrich TM, Castel JR, Holzapfel E, Schulbach H (1982) Drip irrigation saves money in young almond orchards. Calif Agric 36:12–13

Fereres E, Goldhamer D, Sadras V, Smith M, Marsal J, Girona J, Naor A, Gucci R, Caliandro A, Ruz C (2012) Yield response to water of fruit trees and vines: guidelines. In: Steduto P, Hsiao T, Fereres E, Raes D (eds) Crop yield response to water. Irrigation and drainage, vol 66. FAO, Rome. Paper no. 66.

Flexas J, Barón M, Bota J (2009) Photosynthesis limitations during water stress acclimation and recovery in the drought-adapted Vitis hybrid Richter-110 (V. Berlandieri x V. Rupestris). J Exp Bot 60:2361–2377. https://doi.org/10.1093/jxb/erp069

Flexas J, Carriquí M, Coopman RE, Gago J, Galmés J, Martorell S, Morales F, Diaz-Espejo A (2014) Stomatal and mesophyll conductances to CO_2 in different plant groups: underrated factors for predicting leaf photosynthesis responses to climate change. Plant Sci 226:41–48. https://doi.org/10.1016/j.plantsci.2014.06.011

Flexas J, Carriquí M, Nadal M (2018) Gas exchange and hydraulics during drought in crops: who drives whom? J Exp Bot 69:3791–3795. https://doi.org/10.1093/jxb/ery235

Gabaldón-Leal C, Ruiz-Ramos M, de la Rosa R, León L, Belaj A, Rodríguez A, Santos C, Lorite IJ (2017) Impact of changes in mean and extreme temperatures caused by climate change on olive flowering in southern Spain. Int J Climatol 37:940–957. https://doi.org/10.1002/joc.5048

García-Tejero IF, Durán-Zuazo VH, Muriel-Fernández JL (2014) Towards sustainable irrigated Mediterranean agriculture: implications for water conservation in semi-arid environments. Water Int 39:635–648. https://doi.org/10.1080/02508060.2014.931753

García-Tejero IF, Hernández A, Rodríguez VM, Ponce JR, Ramos V, Muriel JL, Durán-Zuazo VH (2015) Estimating almond crop coefficients and physiological response to water stress in semiarid environments (SW Spain). J Agric Sci Tech 17:1255–1266

García-Tejero IF, Moriana A, Rodríguez-PLeguezuelo CR, Durán-Zuazo VH, Egea G (2018a) Sustainable deficit-irrigation management in almonds (Prunus dulcis L.): different strategies to assess the crop water status. Water scarcity and sustainable agriculture in semiarid environment: tools, strategies and challenges for woody crops. Elsevier – Academic Press, London, pp 271–298. ISBN 9780128131640

García-Tejero IF, Gutiérrez-Gordillo S, Souza L, Cuadros-Tavira S, Durán-Zuazo VH (2018b) Fostering sustainable water use in almond (*Prunus dulcis* mill.) orchards in a semiarid Mediterranean environment. Arch Agron Soil Sci 65:164–181. https://doi.org/10.1080/03650340.2018.1492113

García-Tejero IF, Gutiérrez-Gordillo S, Ortega-Arévalo C, Iglesias-Contreras M, Moreno JM, Souza-Ferreira L, Durán-Zuazo VH (2018c) Thermal imaging to monitor the crop-water status in almonds by using the non-water stress baselines. Sci Hortic 238:91–97. https://doi.org/10.1016/j.scienta.2018.04.045

Garrote L, Granados A, Iglesias A (2015) Strategies to reduce water stress in Mediterranean river basins. Sci Total Environ 543:997–1009. https://doi.org/10.1016/j.scitotenv.2015.04.106

Girona J (1992) Estrategias de riego deficitario en el cultivo del almendro. Fruticultura Profesional 47:38–45. ISSN 1131-5660

Girona J (2006) La respuesta del cultivo del almendro al riego. Vida Rural 234:12–16

Girona J, Marsal J, Cohen M, Mata M, Miravete C (1993) Physiological, growth and yield responses of almond (*Prunus dulcis* L.) to deficit irrigation regimes. Acta Hortic 335:389–398. https://doi.org/10.17660/ActaHortic.1993.335.47

Girona J, Arbones A, Miravete C (1997) Evaluation of almond (*Amygdalus communis*) seasonal sensitivity to water stress: physiological and yield responses. Acta Hortic 449:489–496

Girona J, Mata M, Marsal J (2005) Regulated deficit irrigation during the kernel-filling period and optimal irrigation rates in almond. Agric Water Manag 75:152–167. https://doi.org/10.1016/j.agwat.2004.12.008

Gleeson T, Wada Y, Bierkens MFP, van Beek LPH (2012) Water balance of global aquifers revealed by groundwater footprint. Nature 488:197–200. https://doi.org/10.1038/nature11295

Goldhamer DA (1989) Drought irrigation strategies for deciduous orchards. University of California Division of Agriculture and Natural Resources, Berkeley, p 21453

Goldhamer DA, Fereres E (2017) Establishing an almond water production function for California using long-term yield response to variable irrigation. Irrig Sci 35:169–179. https://doi.org/10.1007/s00271-016-0528-2

Goldhamer DA, Girona J (2012) Crop yield response to water: almond. In: Steduto P, Hsiao TC, Fereres E, Raes D (eds) FAO irrigation and drainage paper 66:358–373. Food and Agriculture Organization of the United Nations, Rome

Goldhamer DA, Viveros M (2000) Effects of preharvest irrigation cut off durations and postharvest water deprivation on almond tree performance. Irrig Sci 19:125–131. https://doi.org/10.1007/s002710000013

Goldhamer DA, Viveros M, Salinas M (2006) Regulated deficit irrigation in almonds: effects of variation in applied water and stress timing on yield and yield components. Irrig Sci 24:101–114. https://doi.org/10.1007/s00271-005-0014-8

Griñán I, Rodríguez P, Cruz ZN, Nouri H, Borsato E, Molina AJ, Moriana A, Centeno A, Martín-Palomo MJ, Pérez-López D, Torrecillas A, Galindo A (2017) Leaf water relations in Diospyros kaki during a mild water stress exposure. Agric Water Manag 217:291–398

Grundy MML, Lapsley K, Ellis PR (2016) A review of the impact of processing on nutrient bioaccessibility and digestion of almonds. IJFST 51:1937–1946. https://doi.org/10.1111/ijfs.13192

Gutiérrez-Gordillo S, Durán-Zuazo VH, García-Tejero I (2019a) Response of three almond cultivars subjected to different irrigation regimes in Guadalquivir river basin. Agric Water Manag 222:72–81. https://doi.org/10.1016/j.agwat.2019.05.031

Gutiérrez-Gordillo S, García-Tejero I, García-Escalera A, Galindo P, Arco MC, Durán-Zuazo VH (2019b) Approach to yield response of young almond trees to deficit irrigation and biostimulant applications. Horticulture 2:38. https://doi.org/10.3390/horticulturae5020038

Gutiérrez-Gordillo S, Durán Zuazo VH, García-Tejero IF (2019c) Respuesta agronómica a largo plazo del cultivo del almendro sometido a dos estrategias de riego deficitario. In: XXVIII Congreso Nacional de Riegos, Don Benito (Badajoz). https://doi.org/10.17398/AERYD.2019.A01

Hernandez-Santana V, Fernández JE, Rodriguez-Dominguez C, Romero R, Diaz-Espejo A (2016) The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit. Agric For Meteorol 218:92–101. https://doi.org/10.1016/j.agrformet.2015.11.013

Hsiao TC (1990) Measurements of plant water status. In: Steward BA, Nielsen DR (eds) Irrigation of agricultural crops, Agronomy monograph no. 30. American Society of Agronomy, Madison, pp 243–279

Ibarrola RMJ, Granados RR, Nonhebel S (2017) Is the available cropland and water enough for food demand? A global perspective of the land-water-food nexus. Adv Water Res 110:476–483. https://doi.org/10.1016/j.advwatres.2017.09.018

Idso SB, Jackson RD, Pinter PJ Jr, Reginato RJ, Hatfield JL (1981) Normalizing the stress-degree-day parameter for environmental variability. Agric Meteorol 24:45–55. https://doi.org/10.1016/0002-1571(81)90032-7

IEEP (2018) CAP 2021-27: Proposals for increasing its environmental and climate ambition. Available at: https://ieep.eu/uploads/articles/attachments/63db952e-0825-4eb8-80fe-f88708cfd62f/NABU%20CAP%20Report%20-%20FINAL%20.pdf?v=63710723894

Iglesias A, Buono F (2009) Towards sustainability of water policies in Mediterranean countries: approaches in the SWAP project. Curr Opin Env Sust 1(2):133–140. https://doi.org/10.1016/j.cosust.2009.10.012

Iglesias A, Garrote L (2015) Adaptation strategies for agricultural water management under climate change in Europe. Agric Water Manag 155:113–124. https://doi.org/10.1016/j.agwat.2015.03.014

Iglesias A, Garrote L (2018) Local and collective actions for adaptation to use less water for agriculture in the Mediterranean region. In: Water scarcity and sustainable agriculture in semiarid environment: tools, strategies and challenges for woody crops. Academic Press, London, pp 73–86. ISBN 9780128131640

Iglesias DJ, Cercós M, Colmenero-Flores JM, Naranjo MA, Ríos G, Carrera E (2007) Physiology of citrus fruiting. Braz J Plant Physiol 19:333–362. https://doi.org/10.1590/S1677-04202007000400006

Iglesias A, Mougou R, Moneo M, Quiroga S (2011) Towards adaptation of agriculture to climate change in the Mediterranean. Reg Environ Chang 11:1–8. https://doi.org/10.1007/s10113-010-0187-4

Iglesias A, Garrote L, Quiroga S, Moneo M (2012) A regional comparison of the effects of climate change on agricultural crops in Europe. Clim Chang 112:29–46. https://doi.org/10.1007/s10584-011-0338-8

IPCC (2018) Global warming of 1.5 °C. Intergovernmental Panel on Climate Change, Geneva. http://www.ipcc.ch/report/sr15/

Johnson R, Ayars J, Trout T, Mead R, Phene C (2000) Crop coefficients for mature peach trees are well correlated with midday canopy light interception. Acta Hortic 537:455–460. https://doi.org/10.17660/ActaHortic.2000.537.53

Johnson R, Ayars J, Hsiao T (2001) Modeling young peach tree evapotranspiration. Acta Hortic 584:107–113. https://doi.org/10.17660/ActaHortic.2002.584.12

Jones HG, Serraj R, Loveys BR, Xiong L, Wheaton A, Price AH (2009) Thermal infrared imaging of crop canopies for the remote diagnosis and quantification of plant responses to water stress in the field. Funct Plant Biol 36:978–979. https://doi.org/10.1071/FP09123

Kodad O, Estopañán G, Juan T, Alonso JM, Espiau MT, Socias I, Company R (2014) Oil content, fatty acid composition and tocopherol concentration in the Spanish almond genebank collection. Sci Hortic 177:99–107. https://doi.org/10.1016/j.scienta.2014.07.045

Korres NE, Norsworthy JK, Tehranchian P, Gitsopoulos TK, Loka DA, Oosterhuis DM (2016) Cultivars to face climate change effects on crops and weeds: a review. Agron Sustain Develop 36:12. https://doi.org/10.1007/s13593-016-0350-5

Kumar S, Sheoran S, Kakraliya SK, Kumar P, Meena RS (2016) Drought: a challenge for Indian farmers in context to climate change and variability. Progress Res Int J 11(Special-IX):6243–6246

Kumar S, Karaliya SK, Chaudhary S (2017a) Precision farming technologies towards enhancing productivity and sustainability of rice-wheat cropping system. J Curr Microb and Appl Sci 6 (3):142–151

Kumar S, Lakhran H, Meena RS, Jangir CK (2017b) Current need of sustainable food and forage production to eliminate food and forage insecurity under current climatic era. Forage Rese 44 (1):165–173

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, Singapore, pp 337–375. https://doi.org/10.1007/978-981-13-7264-3_10

Lakhran H, Kumar S, Bajiya R (2017) Crop diversification: an option for climate change resilience. Trends in Biosc 10(2):516–518

Lipan L, Sánchez Rodríguez L, Collado González J, Sendra Nadal EBC, Hernández F, Vodnar DC, Carbonell Barrachina AA (2018) Sustainability of the legal endowments of water in almond trees and a new generation of high quality hydrosustainable almonds. – a review. Food Sci Technol 75:98–108. https://doi.org/10.15835/buasvmcn-fst:2017.0020

Lipan L, García-Tejero IF, Gutiérrez-Gordillo S, Demirbaş N, Sendra E, Hernández F, Durán-Zuazo VH, Carbonell-Barrachina AA (2019a) Enhancing nut quality parameters and sensory profile in three almond cultivars by different irrigation regimes. J Agric Food Chem 68:2316–2328. https://doi.org/10.1021/acs.jafc.9b06854

Lipan L, Martín-Palomo MJ, Sánchez-Rodríguez L, Cano-Lamadrid M, Sendra E, Hernández F, Burló F, Vázquez-Araújo L, Andreu L, Carbonell-Barrachina ÁA (2019b) Almond fruit quality can be improved by means of deficit irrigation strategies. Agric Water Manag 217:236–242. https://doi.org/10.1016/j.agwat.2019.02.041

Lizaso JI, Ruiz-Ramos M, Rodríguez L, Gabaldon-Leal C, Oliveira JA, Lorite IJ, Sánchez D, García E, Rodríguez A (2018) Impact of high temperatures in maize: phenology and yield components. Field Crops Res 216:129–140. https://doi.org/10.1016/j.fcr.2017.11.013

Lobell DB, Gourdji SM (2012) The influence of climate change on global crop productivity. Plant Physiol 160:1686–1697. https://doi.org/10.1104/pp.112.208298

López-López M, Espadafor M, Testi L, Lorite IJ, Orgaz F, Fereres E (2018a) Water requirements of mature almond trees in response to atmospheric demand. Irrig Sci 36:271–280. https://doi.org/10.1007/s00271-018-0582-z

López-López M, Espadafor M, Testi L, Lorite IJ, Orgaz F, Fereres E (2018b) Water use of irrigated almond trees when subjected to water deficits. Agric Water Manag 195:84–93. https://doi.org/10.1016/j.agwat.2017.10.001

Lorite IJ, Gabaldón-Leal C, Ruiz-Ramos M, Belaj A, de la Rosa R, León L, Santos C (2018) Evaluation of olive response and adaptation strategies to climate change under semi-arid conditions. Agric Water Manag 204:247–261. https://doi.org/10.1016/j.agwat.2018.04.008

Mañas F, López FP, López UR (2014) Effects of different regulated and sustained deficit irrigation strategies in almond production. Acta Hort 1028:391–394. https://doi.org/10.17660/ActaHortic.2014.1028.64

Mandalari G, Tomaino A, Arcoraci T, Martorana M, Turco VL, Cacciola F, Rich GT, Bisignano C, Saija A, Dugo P, Cross KL, Parker ML, Waldron KW, Wickham MSJ (2010) Characterization of polyphenols, lipids and dietary fibre from almond skins (*Amygdalus communis* L.). J Food Compos Anal 23:166–174. https://doi.org/10.1016/j.jfca.2009.08.015

Medlyn BE (2011) Comment on drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 333:1093. https://doi.org/10.1126/science.1192666

Meena RS, Kumar S, Yadav GS (2019) Soil carbon sequestration in crop production. In: Meena RS (ed) Nutrient dynamics for sustainable crop production. Springer, Singapore, pp 1–39. https://doi.org/10.1007/978-981-13-8660-2_1

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22. https://doi.org/10.3390/land9020034

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Micke W (1996) Almond production manual. University of California, Berkeley, p 289

Monks DP, Taylor C, Sommer K, Treeby MT (2017) Deficit irrigation of almond trees did not decrease yield. Acta Hortic 1150:251–260. https://doi.org/10.17660/ActaHortic.2017.1150.35

Nakajima H, Behboudian MH, Greven M, Zegbe-Domínguez JA (2004) Mineral contents of grape, olive, apple, and tomato under reduced irrigation. J Plant Nutr Soil Sci 167:91–92

OPM (2019) Scheduling regulated deficit irrigation in a hedgerow olive orchard from leaf turgor pressure related measurements. Agric Water Manag 201:241–252. https://doi.org/10.1016/j.agwat.2015.08.002

Padilla-Díaz CM, Rodríguez-Domínguez CM, Hernández-Santana V, Pérez-Martín A, Fernández JE (2016). Observatorio de precios y mercados Junta de Andalucía. Available: http://www.juntadeandalucia.es/agriculturaypesca/observatorio/servlet/FrontController

Phogat V, Skewes MA, Mahadevan M, Cox JW (2013) Evaluation of soil plant system response to pulsed drip irrigation of an almond tree under sustained stress conditions. Agric Water Manag 118:1–11. https://doi.org/10.1016/j.agwat.2012.11.015

Pou A, Diago MP, Medrano H, Baluja J, Tardaguila J (2014) Validation of thermal indices for water stress status identification in grapevine. Agric Water Manag 134:60–72. https://doi.org/10.1016/j.agwat.2013.11.010

Rani K, Sharma P, Kumar S, Wati L, Kumar R, Gurjar DS, Kumar D, Kumar R (2019) Legumes for sustainable soil and crop management. In: Meena RS, Kumar S, Bohra JS, Jat ML (eds)

Sustainable management of soil and environment. Springer, Singapore, pp 193–215. https://doi.org/10.1007/978-981-13-8832-3_6

Ripoll J, Urban L, Staudt M, Lopez-Lauri F, Bidel LPR, Bertin N (2014) Water shortage and quality of fleshy fruits—making the most of the unavoidable. J Exp Bot 65(15):4097–4117. https://doi.org/10.1093/jxb/eru197

Rodríguez-Domínguez CM, Buckley TN, Egea G, de Cires A, Hernandez-Santana V, Martorell S, Diaz-Espejo A (2016) Most stomatal closure in woody species under moderate drought can be explained by stomatal responses to leaf turgor. Plant Cell Environ 39:2014–2026. https://doi.org/10.1111/pce.12774

Romero P, Botía P, García F (2004) Effects of regulated deficit irrigation under subsurface drip irrigation conditions on vegetative development and yield of mature almond trees. Plant Soil 260:169–181. https://doi.org/10.1023/B:PLSO.0000030193.23588.99

Rouhi V, Samson R, Lemeur R, Van Damme P (2007) Photosynthetic gas exchange characteristics in three different almond species during drought stress and subsequent recovery. EBB 59:117–129. https://doi.org/10.1016/j.envexpbot.2005.10.001

Ruiz-Ramos M, Mínguez MI (2010) Evaluating uncertainty in climate change impacts on crop productivity in the Iberian Peninsula. Clim Res 44:69–82. https://doi.org/10.3354/cr00933

Ruiz-Ramos M, Ferrise R, Rodríguez A, Lorite IJ, Bindi M (2018) Adaptation response surfaces for managing wheat under perturbed climate and CO_2 in a Mediterranean environment. Agric Syst 159:260–274. https://doi.org/10.1016/j.agsy.2017.01.009

Sánchez-Bel P, Egea I, Martinez-Madrid MC, Flores B, Romojaro F (2008) Influence of irrigation and organic/inorganic fertilization on chemical quality of almond (*Prunus amygdalus* cv Guara). J Agr Food Chem 56:10056–10062. https://doi.org/10.1021/jf8012212

Sánchez-Rodríguez L, Corell M, Hernández F, Sendra E, Moriana A, Carbonell-Barrachina ÁA (2019) Effect of Spanish-style processing on the quality attributes of HydroSOStainable green olives. J Sci Food Agric 99:1804–1811. https://doi.org/10.1002/jsfa.9373

Sanden B, Brown P, Snyder R (2012) New insights on water management in almonds. In: Regulatory issues impacting California agriculture. Proceedings. American Society of Agronomy, Visalia, pp 88–93

Schwankl L, Prichard T (2017) Almond irrigation improvement. Continuum 1.0. Almond Board of California 51 pp. Available at: https://www.almonds.com/sites/default/files/misc/grower/almond_irrigation_improvement_continuum_1.0.pdf

Shackel K (2011) A plant-based approach to deficit irrigation in trees and vines. Hortic Sci 46:173–177. https://doi.org/10.21273/HORTSCI.46.2.173

Spinelli GM, Snyder RL, Sanden BL, Shackel KA (2016) Water stress causes stomatal closure but does not reduce canopy evapotranspiration in almond. Agric Water Manag 168:11–22. https://doi.org/10.1016/j.agwat.2016.01.005

Steduto P, Hsiao TC, Fereres E, Raes D (2012) Crop yield response to water. FAO Irrigation and drainage paper 66. FAO, Rome

Tabuenca MC (1977) Winter chilling requirements in almonds. Ann Aula Dei 11:325–329

Teviotdale BL, Goldhamer DA, Viveros M (2001) Effects of deficit irrigation on hull rot disease of almond trees caused by Monilinia fructicola and Rhizopus stolonifer. Plant Dis 85(4):399–403. https://doi.org/10.1094/PDIS.2001.85.4.399

Tójar HJC, Mena RE, Fernández JMA (2017) Spanish agriculture and water: educational implications of water culture and consumption from the farmers perspective. Water 9:964. https://doi.org/10.3390/w9120964

Torrecillas A, Ruiz-Sanchez MC, del Amor F, León A (1988) Seasonal variations on water relations of *Amygdalus communis* L. under drip irrigated and non-irrigated conditions. Plant Soil 106:215–220. https://doi.org/10.1007/BF02371216

Torrecillas A, Alarcón JJ, Domingo R, Planes J, Sánchez-Blanco MJ (1996) Strategies for drought resistance in leaves of two almond cultivars. Plant Sci 118:135–143. https://doi.org/10.1016/0168-9452(96)04434-2

Vu CV (2005) Photosynthesis, growth, and yield of Citrus at elevated atmospheric CO_2. J Crop Improv 13:361–376. https://doi.org/10.1300/J411v13n01_17

Vu CV, Newman YC, Allen LH Jr, Gallo-Meagher M, Zhang MQ (2002) Photosynthetic acclimation of young sweet orange trees to elevated growth CO_2 and temperature. J Plant Physiol 159:147–157. https://doi.org/10.1078/0176-1617-00689

Webber H, Ewert D, Olesen JE, Müller C, Fronzek S, Ruane AC (2018) Diverging importance of drought stress for maize and winter wheat in Europe. Nature Comm 9:4249. https://doi.org/10.1038/s41467-018-06525-2

Williams L, Ayars J (2005) Water use of Thompson seedless grapevines as affected by the application of gibberellic acid (GA 3) and trunk girdling—practices to increase berry size. Agric For Meteorol 129:85–94. https://doi.org/10.1016/j.agrformet.2004.11.007

Xiaoli F, Frederick CM (2018) Metrics and proxies for stringency of regulation of plant water status (iso/anisohydry): a global data set reveals coordination and trade-offs among water transport traits. Tree Physiol 39:122–134. https://doi.org/10.1093/treephys/tpy087

Yada S, Lapsley K, Huang G (2011) A review of composition studies of cultivated almonds: macronutrients and micronutrients. J Food Anal 24:469–480. https://doi.org/10.1016/j.jfca.2011.01.007

Yakushiji H, Nonami H, Fukuyama T, Ono S, Takagi N, Hashimoto Y (1996) Sugar accumulation enhanced by osmoregulation in Satsuma mandarin fruit. Am Soc Hortic Sci 121:466–472. https://doi.org/10.21273/JASHS.121.3.466

Young CT, Schadel WE, Pattee HE, Sanders TH (2004) The micro-structure of almond (Prunus dulcis (Mill.) D.A. Webb cv. 'Nonpareil') cotyledon. LWT-Food Sci Technol 37:317–322. https://doi.org/10.1016/j.lwt.2003.09.007

Zandalinas SI, Mittler R, Balfagon D, Arbona V, Gomez-Cadenas A, Balfagón D (2017) Plant adaptations to the combination of drought and high temperatures. Physiol Plant 162:2–12. https://doi.org/10.1111/ppl.12540

Zimmermann D, Reuss R, Westhoff M, Geßner P, Bauer W, Bamberg E, Bentrup FW, Zimmerman U (2008) A novel, non-invasive, online-monitoring, versatile and easy plant-based probe for measuring leaf water status. J Exp Bot 59:3157–3167. https://doi.org/10.1093/jxb/e

Efficient Groundcovers in Mediterranean Olive Groves Under Changing Climate

20

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Contents

Abstract

Climate change (CC) adaptation represent the main challenge to achieve an equilibrium between sustainability and competitiveness in agricultural systems,

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specially in Mediterranean areas; significant affected by droughts, floods, and a higher frequency of erosive events. The agricultural soil can act as a source or as a sink through soil organic carbon (SOC). Furthermore, it fulfils a fundamental role in water supply, biodiversity, fertility and ecological services. The adoption of effective agricultural practices that conserve the soil and environment and improve its fertility level also helps to mitigate CC by removing atmospheric carbon dioxide (CO_2) (Meena et al., Soil carbon sequestration in crop production. Nutrient dynamics for sustainable crop production. Springer, Cham, 2019). The olive grove is one of the representative crops, which is mostly affected by CC in the Mediterranean area. The use of groundcovers is an efficient tool to protect the soil against erosion, increase organic matter, biodiversity and reduce carbon (C) emissions. Experiments with different types of groundcovers have been conducted in Southern Spain to evaluate the effect on soil protection and their capacity for C sequestration. In an experimental field, seeded gramineous and cruciferous plants were used, in other fields, different legumes and soil managements were compared, and two types of pruning remain mulches were studied in the third field. All treatments were compared with the spontaneous vegetation (SV) of the area. All types of groundcover increased organic carbon sequestration except SV from field 2 where biomass was scarce. Legumes provided generally lower soil cover at the end of the decomposition period than other treatments even though the residues were left on the soil surface after mowing. Due to the fact that high doses were applied, C sequestration was higher in treatments with pruning materials. Therefore, the use of groundcovers is recommendable because they can protect the soil and mitigate CC through SOC sequestration. Seeded groundcovers and pruning remain worked better than spontaneous vegetation, which is the groundcover mostly used by farmers.

Keywords

Cruciferous plants · Gramineous plants · Groundcovers · Leguminous plant · Pruning remains mulch

Abbreviations

%	Percent
BRA	*Brachypodium distachyon*
C	Carbon
CA	Conservation agriculture
$CaCl_2$	Calcium chloride
CC	Climate change
CEC	Cation exchange capacity
cm	Centimetre
CO_2	Carbon dioxide
EC	Electrical conductivity
ERU	*Eruca vesicaria*

EU	European Union
GHGs	Greenhouse gases
H_2O	Water
K	Exchangeable potassium
kg	Kilogram
LSD	Least significant differences
M	Mowing
M+I	Mowing plus incorporation
Mg ha^{-1}	Megagrams (tonnes) per hectare
mg	Milligram
molc	Mol of charge
N	Nitrogen
NH_4^+	Ammonium
NO_3^-	Nitrate
N_T	Total nitrogen
OC	Organic carbon
OM	Organic matter
P	Available phosphorus
Pg	Petagrams (gigatonnes)
pH	Puissance of hydrogen ions
PR	Pruning remains mulch
PR1	Pruning remains mulch (dose 1)
PR2	Pruning remains mulch (dose 2)
SIN	*Sinapis alba*
SOC	Soil organic carbon
SV	Spontaneous vegetation
SV1	Spontaneous vegetation field 1
SV2	Spontaneous vegetation field 2
SV3	Spontaneous vegetation field 3
VER	*Vicia ervilia*
VSA	*Vicia sativa*
VVI	*Vicia villosa*

20.1 Introduction

Agriculture is the productive activity mostly depending on climate change (CC) as there is a direct relationship between agricultural activities and the climatic conditions (Carbonell-Bojollo et al. 2019). Changes in temperatures and rainfall and the increase in atmospheric carbon dioxide (CO_2) concentration significantly affect the crop development (Lal 2004; Rani et al. 2019).

Climate change affects the agricultural sector in different ways depending on the region in which crops are grown as it depends on exposure to adverse climatic characteristics and their ability to adapt to them (Donatelli et al. 2012; Iglesias et al. 2012; Gupta and Kumar 2018; Kumar et al. 2019). It should also be noted that not all

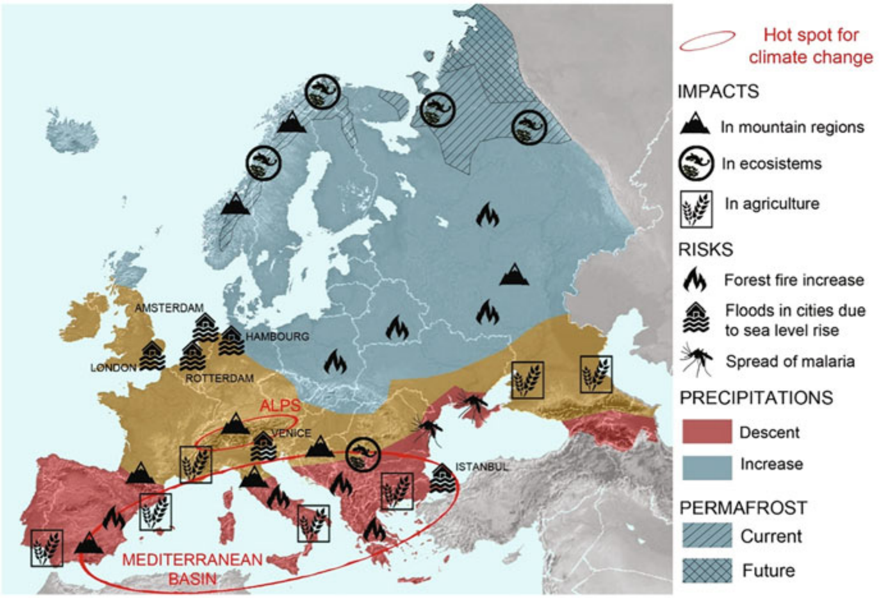

Fig. 20.1 Consequences of climate change in Europe (Adapted, Márquez-García 2017)

actions derived from this CC are adverse, but some may be beneficial, such as the increase in growing seasons in higher latitudes and montane ecosystem (Kang et al. 2009). On the contrary, some of the expected adverse effects of CC are lack of water and frequent and intense extreme weather events (Newton et al. 2011; Meena et al. 2016, 2017).

The European Commission (2009) identifies the regions of Southern Europe as the most sensitive cultivated area to CC, anticipating a decrease in crop productivity. Most importantly, the countries with a Mediterranean climate are more susceptible to the adverse effects of CC because the climatic phenomena like multiannual droughts, irregular precipitation, high summer temperatures, heatwaves, summer drought, floods, etc. become more intensified as the temperature rises (Ciscar et al. 2011; Kumar et al. 2016). Figure 20.1 summarises the foreseeable consequences of the CC on European agriculture, showing that the Mediterranean arc will be the region in which the resulting conditions may be more adverse (Márquez-García 2017).

In this context of CC, Mediterranean agriculture will be the most affected by the lack of rainfall, increase in temperatures, and other torrential events (Kovats et al. 2014; Kumar et al. 2020). Extreme rainfall events will increase erosion processes resulting in loss of soil and water quality which will reduce the cultivable areas (García-Ruiz et al. 2011; Olesen et al. 2011). Tables 20.1 and 20.2 shows that in the Mediterranean region, practically all the adverse effects derived from the climatic change present a high risk, while the beneficial aspects present only medium

Table 20.1 Degree of certainty for each risk based on each agroclimatic zone (adapted, Márquez-García 2017)

Risks	Boreal	Atlantic	Continental	Alpine	Mediterranean
Changes in cropland area, due to a decrease in the optimal conditions for its development	(No effect)	Medium	Medium	Medium	High
Crop productivity decline	(No effect)	Medium	Medium	Medium	Medium
Increased risk of agricultural pests, diseases, or weeds	High	High	High	Medium	High
Crop quality decline	(No effect)	Medium	Medium	(No effect)	High
Increased flood risk	High	High	High	High	(No effect)
Increased risk of drought and water shortage	(No effect)	High	High	High	High
Increased irrigation needs	(No effect)	Medium	High	(No effect)	High
Water quality deterioration	High	High	(No effect)	High	(No effect)
Soil erosion, salinisation, desertification	High	Medium	High	High	High
Loss of glaciers and permafrost (soils with ice, which act as a water reserve)	Medium	(No effect)	(No effect)	High	(No effect)
Deterioration of conditions for livestock production	High	Low	Low	High	Medium
Sea level rise	High	High	High	(No effect)	High

opportunities. In summary, among the five regions listed in Tables 20.1 and 20.2, Mediterranean is the one with the worst prospects in Europe.

Farmers being the crucial component of the rural economy fulfil an essential role in the management and maintenance of European biodiversity. Therefore, the regulatory measures adopted to address this food and the environmental problem must take into account the environmental impact of agriculture and its socio-economic importance for many communities.

In other words, a severe environmental problem is affecting the European Union (EU) generally speaking and concretely in the Mediterranean area, with consequences at various levels, which will be especially adverse in agricultural ecosystems. Therefore, the characteristics of agriculture make it both a source of greenhouse gases (GHGs) emissions and a recipient of the effects of CC impacts.

Table 20.2 Degree of certainty for each opportunity based on each agroclimatic zone (Adapted, Márquez-García 2017)

Opportunities	Boreal	Atlantic	Continental	Alpine	Mediterranean
Changes in crop distribution to optimise conditions	High	Medium	High	High	Medium
Increase crop productivity	Medium	Medium	(No effect)	High	(No effect)
Water availability	High	High	(No effect)	Medium	(No effect)
The decrease in energy costs for greenhouses	Medium	Medium	Medium	(No effect)	Medium
Improvement of livestock productivity	High	High	High	High	(No effect)

Since it is causative and, at the same time, an affected party, there has been a great interest to perform mitigation and adaptation measures on this sector as recognised in different legislation.

According to the Communication COM (2010), 672/5 of the European Commission, agriculture plays a fundamental role in the provision of public goods, and especially in those related to the environment and climate stability. This is because this sector has great importance in energy consumption and emissions of GHGs. European Union is carrying out in this field the Europe 2020 Strategy to achieve a reduction of 20% (or 30% if possible) of GHGs emissions. Therefore, European policies related to the objective of CC and energy suggest mitigating CC by increasing carbon (C) sequestration potential of the soil and reducing energy consumption using different management practices, as reflected in the future common agricultural policy.

Currently, agricultural lands have been degraded and lost, while on the another side, the concentration of GHGs in the atmosphere is continuing to increase. Many worldwide regions are turning into the desert and every year 3.4 tons of fertile soil per inhabitant is lost globally. At this tendency, according to the United Nations, fertile soil will be reduced by half in 2050. Also, this whole panorama takes place in the context of a growing population of 10,000 million people (UN 2008). Since the beginning of the industrial revolution, the soil organic carbon (SOC) has been reduced by half.

However, we have a great ally against climate change. It is estimated that the soils have the potential to store more than three times the C in the atmosphere at the first metre of its depth. The soils could restore the lost organic carbon (OC) by removing it from the atmosphere. The United Nations (UNEP 2012) pointed out that soil C plays a vital role in the regulation of climate, water supply and biodiversity, and it is also essential for ecological services for human well-being. The scenario we are facing right now shows a 50% increase in food demand, 35–50% in water demand and 45% in energy demand (UNEP 2012).

Climate change is one of the factors that can convert the soil from a C sink into a source of emissions but not the only one (Meena et al. 2020a, b). The way we use the soil also influences the amount of C that the soil can retain. In general, the adoption of appropriate agricultural and forestry practices that take into account the conservation of natural resources and the protection of the environment can protect the soil and remove a large amount of CO_2 from the atmosphere.

The soil, as a means of the fundamental factor for food production, is considered to be one of the essential natural resources for the socio-economic development of a country. It is a limited resource with great value, and the irreversible degradation of this resource means not only destroying the most precious possession of farmers but also mortgaging future agricultural opportunities. Therefore, we need to maintain its productivity, through proper management and implementation of suitable agricultural practices, considering it as a long-term renewable resource that guarantees its fertility and its agronomic value, in the present and future. The degradation of the soil is conditioned by the action of several processes, such as pollution, erosion, acidification, salinisation and loss of soil structure (Meena et al. 2020a). These phenomena are caused by the inadequate management of the soil, such as deforestation, intensification of the agricultural land, abuse of the soil tillage, inappropriate use of heavy machinery, use of uncontrolled inorganic fertilisers and monoculture.

In recent years, the soil has been recognised as the most massive C sink in the context of its global cycle, where agricultural activities acquired particular importance, due to its extension and the numerous options it presents to fix or emit C (Kimble et al. 2003; González-Sánchez et al. 2012; Lal 2014). Smith (2007) and Smith et al. (2008) have studied the possibilities of mitigating GHGs emissions from agricultural practices, concluding that about 90% of the total mitigation potential is derived from C sequestration from the soil. Soil organic carbon participates in four primary ecosystem services: it provides soil resistance to erosion, increases its water retention capacity, increases its fertility for plants and favours the biodiversity. The minimal evolution of soil C stock generates very significant effects on agricultural productivity and the global cycle of GHGs. Therefore, preserving and increasing SOC restoring and improving degraded agricultural soils lead to adapt food systems and populations to CC effects, while the increased food demand is covered, and anthropogenic emissions are offset. The amount of C accumulated in the soil is estimated at around 2500 Pg (Peta grams), much higher than stored in the atmosphere and biotic mass, i.e. 760 and 560 Gt, respectively (Lal 2004). Photosynthetic assimilation of atmospheric CO_2 by plants is also imperative (Peterhansel and Offermann 2012; Rogaard et al. 2012; Ávila et al. 2014).

Carbon sequestration requires stabilising C in the soil in segments or structures of low degradability so that it is not immediately reissued. Since the degradation of organic matter (OM) in the soil can last for even millennia (Paul et al. 1997; Torn et al. 1997), increasing the SOC through proper soil management practices is an attractive option as the strategy of fixing or sequestering C in the soil is effective economically and environmentally. Carbon sequestration by agricultural soils is an essential factor to be considered while designing future CC mitigation and adaptation strategies. In this sense, the current agriculture must be directed towards soil management that improves the OM content and promotes the capturing of C into the soils, through the implementation of agricultural practices such as those related to agroecology, conservation agriculture (CA) and crop rotation.

The practices that increase the intake of atmospheric C by the plant and slow its release in the form of atmospheric CO_2 or reduce soil erosion will improve the carbon sink effect of the soil. In general, the sequestration of C in the soil will be favoured by reducing the frequency and intensity of tillage. Likewise, maximising the quantity of crop residues that return to the soil will promote soil protection reducing soil erosion. Besides, agricultural practices such as rotation of annual crops, groundcovers in woody crops and controlled application of organic amendments foster soil C stock.

The soil management system used in crops powerfully influences the rate of C sequestration, the efficiency of its use and the respiration of the soil (Triplet and Dick 2008; Kassam et al. 2012; González-Sánchez et al. 2015). The different tasks carried out on agricultural land will influence both the fuel consumed and the amount of CO_2 emitted into the atmosphere as a result of the OM oxidation (Ordóñez-Fernández et al. 2007a; Carbonell-Bojollo et al. 2011). Practices promoted by CA could be a possible solution to these issues because they can reduce the used fuel (Hernanz et al. 1995; Nassi Di Nasso et al. 2011) and increase the C sink effect of the soils (González-Sánchez et al. 2012; Márquez-García et al. 2013; Carbonell-Bojollo et al. 2015).

In Southern Spain, under the Mediterranean climate, agricultural soils are prone to erosion processes due to loss of the arable layer, and therefore they usually have low OM content. Under these premises, the inadequate use of agricultural machinery can further increase its erosion and reduce its quality. A beneficial alternative for the farmer would be the implementation of conservation tillage systems since they include a series of soil management techniques that make the system more productive and sustainable contributions to the maintenance and recovery of natural soil, water and air resources. The implementation of these techniques can benefit farmers economically (energy saving), while in the long run, it produces environmental benefits by improving the quality of the soil–water–plant system and maintaining its characteristics.

One of the agricultural techniques used for sustainable agricultural development is the implementation and use of cover crops between growing season of annual crops or groundcovers in the inter-rows of woody crops, according to the nomenclature proposed by González-Sánchez et al. (2015). They protect the soil against erosion, increase the OM content and soil biodiversity, improve water quality and decrease CO_2 emissions into the atmosphere. Although cover crops/groundcovers were initially proposed for protection against erosion (Ordóñez-Fernández et al. 2007a; Krutz et al. 2009) and N leaching (Quemada et al. 2013), lately they have been studied to mitigate and adapt to CC (Vicente-Vicente et al. 2016; Kaye and Quemada 2017), among others ecosystem services (Blanco-Canqui et al. 2015).

In the Mediterranean region, the most important cause of soil erosion is rainwater. The two most important factors are the force of the rain impacting on the ground and the speed of the runoff water, which drags the earth into its natural channel.

20.2 Current Situation in Mediterranean Olive Groves

In the Mediterranean area, woody crops have undergone a significant advancement (EUROSTAT 2016). Notably, being the oldest crop in this region, the olive tree (*Olea europaea* L.) has suffered an enormous expansion (Barranco et al. 2008). Thus, the olive tree best represents the Mediterranean area because of its economic, social and environmental importance. In Spain, it occupies 2.7 million hectares, with 60% of the Spanish olive groves (1.6 Mha) concentrated in Andalusia (MAPA 2018).

Currently, one of the biggest problems of olive groves is the high rate of SOC loss due to the application of conventional agricultural practices such as intensive ploughing, the removal of herbaceous cover and the use of pesticides and chemical fertiliser (Repullo-Ruibérriz de Torres et al. 2018). All this has also caused the reduction of the CO_2 sink capacity of the olive grove ecosystem with the consequent environmental damage and high economic cost.

A large part of the agricultural area destined to the olive grove is located in regions with steep slopes, in which the management system consists of farms with sizeable traditional plantation frameworks in the dry land regime (Gómez et al. 2009). In this type of farm, a large area of land is not occupied by the crop and, therefore, it is more exposed to climate events. Thus, large volumes of precipitation are accompained of soil particles dragging, taking away the most fertile layers of the soil. These erosive processes cause massive amounts of soil loss that can reach 25 Mg ha^{-1} annually. The soil, which is displaced by the effects of erosion and runoff, is sometimes transported reaching the channels of the seas and rivers, causing chemical elements contamination and sediment accumulation. When the flow of runoff increases, it can form gullies that might cause loss of trees and accessibility problems on farms, resulting in severe economic losses for the farmer (De Baet et al. 2009).

The soil loss, due to erosive processes, implies economic and environmental losses. Therefore, in most of the Mediterranean regions, olive grove is considered as eco-inefficient (Gómez-Limón and Arriaza 2011), because of the serious erosive processes caused by the constant and intensive tillage practice (Vanwalleghem et al. 2010; Gómez et al. 2011; Taguas et al. 2011), which makes this process the most significant environmental problem of olive growing (García-Ruiz et al. 2011). Sediments also influence the loss of C as it is transported and subsequently emitted into the atmosphere, estimating that CO_2 emissions associated with erosion are between 0.8 and 1.2 Pg $year^{-1}$ worldwide (Lal 2003). We must also bear in mind the GHGs emissions that are generated as a result of the oxidation of OM caused by tillage (Carbonell-Bojollo et al. 2011) lead to depletion of C stock of soil under olive cultivation (Márquez-García et al. 2013). All these factors show olive groves are very vulnerable to CC and are affected by desertification processes provoked by excessive tillage, loss of fertility and decreased soil moisture (Fernández-Romero et al. 2014).

Therefore, considering the fragility of olive grove against the CC, it is necessary to undertake measures that favour mitigation and adaptation to the harmful effects of

CC on this crop. The CA systems in woody crops, groundcovers are considered to be a beneficial technique for such purposes, providing a significant number of agro-environmental benefits, without increasing production costs (Márquez-García et al. 2013) and reducing the number of products (Barranco et al. 2008). Reduced erosion is one of the main benefits of CA systems, and precisely for this reason, they were implanted by olive growers. Besides, they also reduce runoff (Francia et al. 2006; Ordóñez-Fernández et al. 2007a; Gómez et al. 2009) and contamination of surface waters (Franklin et al. 2007; Ordóñez-Fernández et al. 2007a), improving the water balance of the olive groves (Durán-Zuazo et al. 2009; Alcántara et al. 2011), increasing the OC content (Moreno et al. 2009; Carbonell-Bojollo et al. 2011; Márquez-García et al. 2013) and the soil microbial activity and its biodiversity. It is noteworthy that this technique applies to the vast majority of fruit trees, even in cultivated vines with significant soil loss (González-Sánchez et al. 2015).

The CA systems in woody crops, based on the use of groundcovers, accumulate C in the soil as it decreases the OM output associated with sediment by reducing water erosion (Gómez et al. 2005; Francia et al. 2006; Ordóñez-Fernández et al. 2007a, b), increase the OM content (Moreno et al. 2009) and decrease its mineralisation by not aerating the land and improving its structure (Oades 1993; Franzluebbers 2002).

When the farmer decides to leave groundcovers on their farm, they can do it on the entire field or only in the centre of tree rows. It is crucial in the latter case that the groundcover is established in the perpendicular direction to the maximum slope line. The groundcover should occupy the maximum possible space so that it can perform their function and the farmer must maintain it throughout the year, paying particular attention to it at the time when it can compete with the tree for water. This point will be decisive when choosing the variety of the groundcover and the time to mow it. The kill date is critical (Alonso-Ayuso et al. 2014), groundcovers take up nutrients limiting leaching at the living stage but competition with olive trees, mainly in the flowering phenological phase, should be avoided.

The establishment of groundcovers prevents mechanical operations on the ground, so the soil particles are added in a stable way forming a good soil structure, favouring the infiltration and distribution of rainwater in the layers of the soil. The protection offered by groundcovers against the impact of the raindrops and the reduction of runoff water decreases erosion risks very effectively, sometimes up to 95% (Repullo-Ruibérriz de Torres et al. 2018). Therefore, the use of this technique helps to achieve healthy soils that have life, and, ultimately, improve the sustainability of agricultural systems.

20.3 Different Groundcovers and Soil Carbon Sequestration

20.3.1 Different Types of Groundcovers

González-Sánchez et al. (2007) identified the following basic types of cover according to their establishment:

- Spontaneous vegetation groundcover: It consists of the natural regional flora in the area that grows spontaneously. These types of vegetations are dominant in the Mediterranean area because of their economic flexibility. In some areas, it is the only option due to topography. About 92% of the olive groves that use any groundcover in Spain (about 30% surface of olive groves) use spontaneous vegetation (MAPA 2018). The farmers leave plant growth without control until spring season when the cover competes with olive trees for water and nutrients. Sometimes, a specific broadleaf herbicide is spread in the first stages to select narrow-leaf species such as gramineous plants that are controlled more quickly in spring. To regrow the following season, a strip of the groundcover must be left to germinate providing a seed bank.
- Seeded cover: These are recommended for soils that have been tilled previously or managed by pre-emergence herbicide (bare soil). In this case, there is a scarce seed bank where spontaneous vegetation is not enough to protect the soil from erosion. Although they offer many benefits, seeded groundcovers represent only 1% of the surface of olive groves in Spain with groundcover (MAPA 2018).
  - Grass groundcovers: Gramineous plants provide high soil coverage but they do not show much vigorous growth that narrows down the competition with olive trees (Saavedra and Pastor 2002). Furthermore, they can be easily controlled by the standard herbicide in spring. The common grasses used in Mediterranean areas are barley (*Hordeum* ssp.), oat (*Avena* spp.), ryegrass (*Lolium* ssp.), brome (*Bromus* spp.) and *Brachypodium distachyon* (BRA). These latter two species are considered permanent groundcovers because of their short cycle and high capacity to self-seed from a groundcover strip left alive in the previous season.
  - Crucifers: Being more competitive with olive trees than grasses, crucifers are recommended because of two main aspects. First, they have a robust root system that alleviates compaction (Wolfe 2000) and, on the other hand, they are used for phytosanitary purposes due to the high glucosinolates content. Glucosinolates are composed of sulphur and have a toxic effect on some phytopathogens such as *Verticillium dahliae* (Shetty et al. 2000) which is one of the most significant phytopathological problems of olive grove (Roca et al. 2016). Brassica species have fast growth and also provide high soil coverage and biomass in a short period. Some of the most studied species are *Sinapis alba* subsp. *mairei*, *Eruca vesicaria* (ERU), *Raphanus sativus* and *Brassica carinata* (Alcántara et al. 2011).
  - Legumes: Leguminous plants are appropriate groundcovers for their potential to fix atmospheric nitrogen, this allows using them as green manure (Guzmán Casado and Alonso Mielgo 2001) improving fertility and microbial activity (Stagnari et al. 2017). Their low C/N ratio leads to a fast decomposition and N release; however, legumes could leave the soil bare/unprotected for a longer period compared to the species of other families. Therefore, they are not recommended for fighting against erosion (Ordóñez-Fernández et al. 2018). Vetches (*Vicia* spp.), clovers (*Trifolium* spp.), *Medicago* spp. and *Lathyrus* spp. are the most frequently used as groundcovers in Mediterranean areas.

- Inert cover mulch: They are non-living elements such as pruning remains, leaves or stones, so they are not competitive with olive trees for water and nutrients. To eliminate the risk of bark beetles (*Phloetribus scarabaeoides*), pruning remains should be shredded by chopper machine. Chopped pruning remains used as mulch entails an extended-lasting and non-competitive cover that also works as an organic amendment. Moreover, the high amounts that are usually managed affect reducing weeds, acting as a herbicide. In the case of trees affected by a disease, pruning material should be removed to reduce spread potential. The surface area of olive groves with this type of cover makes up 7% of the total surface of olive groves with groundcover in Spain (MAPA 2018).

Every year, the surface of the olive grove is increasing in Spain, but the ratio of olive grove with groundcovers is about 30%, growing quite steadily. Within this 30%, mulching based on pruning remains has increased its fraction from 4 to 7% in 5 years due to its various advantages (MAPA 2018).

20.3.2 Soil Carbon Sequestration, Field Experiments Through Groundcovers

Through different studies, the efficiency of groundcovers is quantified as a method to improve the capacity of the soil for C sink in olive groves regions of semi-arid conditions. Three experimental fields were set up within which different types of groundcovers were grown and studied during four seasons (Fig. 20.2). To assess the C sequestration potential of several species from three different families used as groundcovers, experimental fields 1 and 2 were conducted in two olive orchards considering spontaneous vegetations in both the fields. In field 3, pruning remains mulches as inert cover were compared to spontaneous vegetation.

The initial hypothesis of the work considers that the more C input provided by groundcovers, the more SOC will be fixed into the soil. It is also expected that seeded groundcovers would produce a higher amount of biomass than spontaneous vegetation. Likewise, pruning remains mulch means more amount of biomass and C than spontaneous vegetation.

20.3.2.1 Experimental Field 1: Grass, Crucifers and Spontaneous Vegetation

In this field, a sown grass called ‘Vegeta’ (*Brachypodium distachyon* L.) (BRA) and two cruciferous species, rocket (*Eruca vesicaria* (L.) Cav.) (ERU) and regular mustard (*Sinapis alba* L. subsp. *Mairei* (H. Lindb. Fil.)) (SIN) were studied. The spontaneous vegetation from field 1 (SV1), that is, typical weed flora of the area mainly composed by mallows, *Convolvulus arvensis*, *Diplotaxis virgata*, *Picris echioides*, *Lolium rigidum*, *Fumaria parviflora* and *Taraxacum officinale* was considered as the control treatment.

The experiment was carried out in ‘Arenillas Farm’ close to Fernán Núñez village in Córdoba province, Southern Spain, whose coordinates are 37°40′2″ N and

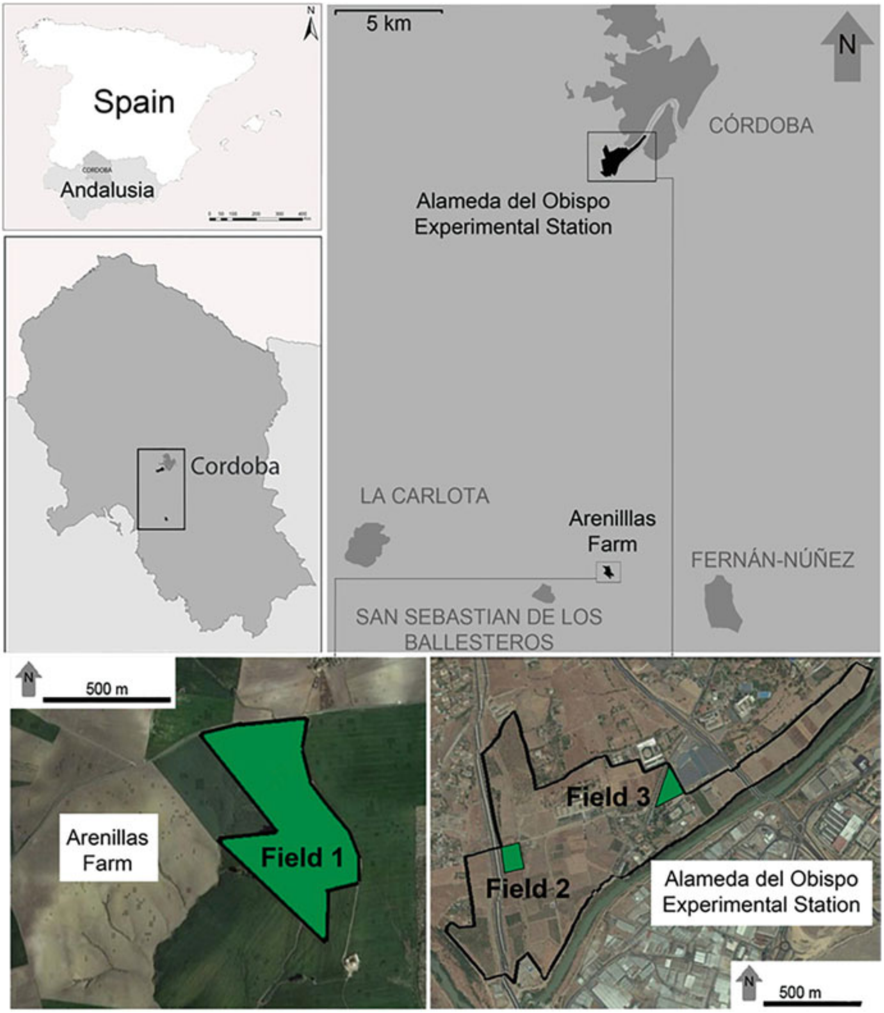

Fig. 20.2 Location of the three experimental fields with some type of groundcover

4°47′5″ W and the elevation is 265 m above mean sea level. The plot has an 11% average slope and the soil is a *Vertic haploxerept* (Soil Survey Staff 2014). The physicochemical characteristics of the soil are shown in Table 20.3. The experiment was conducted during four growing seasons (2008–2011).

The cultivated olive trees are ‘Picual’, and they were planted five years before the experiment at a distance of 4 × 8 m^2. The soil had been conventionally tilled with a disc harrow two or three times per year.

Eruca vesicaria and *Sinapis alba* seeds were previously collected from natural wild populations and replicated in the Andalusian Research Centre, IFAPA Alameda del Obispo (Córdoba, Spain). Cruciferous seeds were sown every season at doses of

Table 20.3 Physicochemical characteristics of the soil of experimental field 1

Depth (cm)	pH (H_2O)	pH ($CaCl_2$)	Sand (%)	Silt (%)	Clay (%)	Textural class
0–10	8.14	7.66	6.0	43.5	50.5	Silty clay
10–20	8.23	7.66	9.8	39.1	51.1	Silty clay
20–40	8.28	7.68	8.4	41.7	49.9	Silty clay
40–60	8.36	7.74	8.8	41.8	49.4	Silty clay
Depth (cm)	OM (%)	$CaCO_3$ (%)	N_T (%)	P (mg kg^{-1})	K (mg kg^{-1})	CEC (mol_c kg^{-1})
0–10	0.85	29.88	0.04	06.51	326.20	0.24
10–20	0.72	28.50	0.03	13.60	369.45	0.22
20–40	0.65	31.75	0.02	09.86	271.75	0.23
40–60	0.58	33.06	0.02	10.95	209.67	0.22

OM organic matter, N_T total nitrogen, *P* available phosphorus, *K* exchangeable potassium, *CEC* cation exchange capacity, *pH* puissance of hydrogen ions, H_2O water, $CaCl_2$ calcium chloride, *cm* centimetre, *%* percent, *mg* milligram, *kg* kilogram, mol_c mol of charge

10 and 3 kg ha^{-1} for SIN and ERU, respectively, at 0.5 cm depth following the procedures established in previous field experiments (Alcántara et al. 2009). Before the sowing of crucifers, the crop residues of the previous season were buried in soil with a pass of disc harrow. *Brachypodium distachyon* was only sown the first year at a rate of 100 kg ha^{-1} of a commercial product, which meant 30 kg seeds ha^{-1} since it was commercialised with fertiliser, then seeds were left on the surface following commercial recommendations. Next year, BRA was established from a groundcover strip which had been left alive the first year to self-seed.

One experimental unit consisted of a groundcover strip placed in the inter-row with a size of 12 m (distance between four olive trees in a row) in length and 4 m in width. In the groundcover area, two mowings were conducted by a flail mower during the spring season. This machine with a horizontal axis allows a more homogeneous distribution of the residues than those that have a vertical axis which has a particular wind-rower effect (Ordóñez-Fernández et al. 2018). The weeds under canopies (4 m wide in trees row) were controlled by systemic herbicide (glyphosate 36%) in spring. The fertilisation in the farm consisted of 200 kg ha^{-1} of urea (46% N) spread onto the soil in February every year.

20.3.2.2 Experimental Field 2: Legumes and Spontaneous Vegetation

In this study, three leguminous plants commonly vetch (*Vicia sativa* L.) (VSA), bitter vetch (*Vicia ervilia* L.) (VER) and hairy vetch (*Vicia villosa* Roth.) (VVI) that are typically used as a groundcover in Mediterranean areas were studied. They were settled and compared with spontaneous vegetation that grew naturally in the field (SV2). The mainly identified species were: *Medicago polymorpha*, *Bromus* sp., *Diplotaxis virgata*, *Anagallis arvensis* and *Hordeum* spp.

This study was carried at field F located in the IFAPA (Andalusia Research Centre) ‘Alameda del Obispo’ Experimental Station near the Guadalquivir River in Cordoba (Spain) whose coordinates are 37°51′25″ N and 4°48′28″ W. The slight

Table 20.4 Physicochemical characteristics of the soil of experimental field 2

Depth (cm)	pH (H_2O)	pH ($CaCl_2$)	Sand (%)	Silt (%)	Clay (%)	Textural class
0–10	8.71	7.73	57.7	26.5	15.9	Sandy loam
10–20	8.86	7.83	57.0	27.3	15.7	Sandy loam
20–40	8.82	7.84	56.2	28.2	15.5	Sandy loam
40–60	9.11	8.05	62.6	25.3	12.0	Sandy loam
Depth (cm)	OM (%)	$CaCO_3$ (%)	N_T (%)	P (mg kg^{-1})	K (mg kg^{-1})	CEC (mol_c kg^{-1})
0–10	2.30	15.73	0.06	06.97	263.11	0.14
10–20	1.96	15.76	0.04	02.79	178.03	0.13
20–40	2.07	15.38	0.03	05.12	150.73	0.13
40–60	1.37	20.90	0.03	02.32	108.73	0.13

OM organic matter, N_T total nitrogen, *P* available phosphorus, *K* exchangeable potassium, *CEC* cation exchange capacity, *pH* puissance of hydrogen ions, H_2O water, $CaCl_2$ calcium chloride, *cm* centimetre; % percent, *mg* milligram, *kg* kilogram, mol_c mol of charge

average slope of the experimental plot is 2%, and it has 95 m of elevation. The soil is classified as *Typic calcixerept* according to Soil Survey Staff (2014). The physicochemical characteristics of the soil are shown in Table 20.4.

The olive trees belonged to the ‘Picual’ cultivar and were planted 12 years before with a plantation pattern of 6 × 5 m^2. Before the experiment started, the soil had been treated with pre-emergence herbicide, but in the previous season, no management was done on the soil.

Legumes are widely used in organic farming to supply the biologically fixed N. A usual practice carried out by farmers consists of leaving leguminous plants on the soil to accelerate the decomposition and the availability of N for olive trees. For this reason, the experimental design used was split-plot, being the species main factor and soil management sub-factor. Each block included two inter-rows to compare the soil management systems after the mechanical mowing of the groundcover. In one of the olive trees inter-rows, plant residues were buried into the soil by a disc harrow pass calling this management mowing plus incorporation (M+I), in the other inter-row the residues were left on the surface to decompose as mulch, the groundcovers were only mowed so this management was call mowing (M). The mowing was performed once by a flail mower at the end of April every year.

The single plots consisted of the distance between two trees with one central olive tree in a row and a groundcover strip of 10 × 3.5 m^2 to each side. The width of the cover strip was 3.5 m, corresponding to the width of the cultivator. The legumes were seeded every season at the rate of 200 kg ha^{-1} and buried slightly. In each season before the sowing, legumes and SV2 residues of the previous season in M management were buried into the soil by a disc harrow pass. The weeds in the olive trees row strip (2.5 m wide) were controlled by systemic herbicide (glyphosate 36%) in spring at the rate of 4–5 L ha^{-1}.

In both the experimental fields, the biomass of the groundcovers was measured in a square frame of 0.25 m^2 randomly placed in each subplot. In order to calculate the

Table 20.5 Carbon released (kg ha^{-1}) from the residue of each groundcover in every season during the 4-year study period in field 1 (C content in biomass at mowing date for the first three seasons and C released at the end of the decomposition period in the fourth season)

	C release in field 1			
Season	BRA	ERU	SIN	SV1
1	2994.2	1281.1	1519.0	901.8
2	4602.2	3102.4	2808.8	2786.3
3	1550.5	1680.7	2229.6	2294.8
4	712.4	547.9	919.9	523.2
Total	9859.3	6612.0	7477.2	6506.0

BRA *Brachypodium distachyon*, ERU *Eruca vesicaria*, SIN *Sinapis alba*, *SV1* Spontaneous vegetation (field 1)

C input provided by the groundcovers, total C in the biomass samples was analysed in a LECO elemental analyser (TRUSPEC, CNS; St. Joseph, MI, USA). The soil cover of residues was also measured following the Subjective Valuation Per Sector Method (Moreno-García et al. 2018), using a frame of 1 m^2 divided into 100 grids. The soil cover in the M+I management in field 2 was not able to monitor as residue had been buried. The soil was sampled at a depth of 0–5, 5–10 and 10–20 cm using an Edelman auger. Also, core cylinders of known volume were used to take undisturbed soil samples in order to measure the bulk density. The soil samples were air-dried and sieved through a 2 mm mesh sieve for their subsequent analysis. Soil organic carbon was analysed by Walkley–Black chromic acid wet oxidation method (Walkley and Black 1934). The amount of sequestered C in soil was estimated from the increment of SOC in the entire 4-year experiment. The atmospheric CO_2 fixation was estimated from SOC increment data using the molecular weight ratio (1 g C = 3.67 g CO_2).

The pattern of decomposition can be explained considering the specific soil and climate conditions, the soil management practice and the composition of the different species. A faster decomposition is expected in the case of legumes due to the lower CN ratio (Ordóñez-Fernández et al. 2007b).

Carbon is the main element in plant residues, containing about 42% of dry matter (Robertson and Thorburn 2007), so it is substantially released while the residue is decomposed. It must be highlighted that legumes and crucifers' residues before sowing of the new season were buried by a disc harrow what could enhance the C release in the growing stage of the new season. However, BRA and SV1 residues were not incorporated, thus they were gradually decomposed during the following season. Assuming that the residue of the previous season is decomposed completely before the mowing date, the total amount of released C will depend on the maximum biomass reached in the developing period. In the four-season study, BRA was the species which released the enormous amount of C in field 1 (Table 20.5) and VVI in field 2 (Table 20.6).

The excellent C input provided by VVI in M and M+I systems must be highlighted. Although legumes were sown at a higher rate than the species in field 1, it shows a higher production than other leguminous groundcovers that were sown

Table 20.6 Carbon released (kg ha^{-1}) from the residue of each groundcover in every season during the 4-year study period in field 2 (C content in biomass at mowing date for the first three seasons and C released at the end of the decomposition period in the fourth season

	C release in field 2							
	M				M+I			
Season	VSA	VER	VVI	SV2	VSA	VER	VVI	SV2
1	2587.9	2565.8	2602.4	559.7	2837.0	1736.2	2352.6	989.0
2	2732.1	1531.3	3443.3	995.1	2808.8	2469.5	3391.6	794.5
3	2015.0	969.2	4455.9	1055.6	1408.8	1203.7	1903.5	1506.3
4	1693.0	814.1	1778.6	1935.5	1054.7	1659.0	2165.4	1934.6
Total	9028.1	5880.5	12,280.2	4545.9	8109.3	7068.4	9813.1	5224.5

VSA *Vicia sativa*, VER *Vicia ervilia*, VVI *Vicia villosa*, *SV2* Spontaneous vegetation (field 2)
Total decomposition of residue is assumed at the end of decomposition period in the fourth season with M+I)

at the same doses. By the contrary, the spontaneous vegetation in field 2 had a little amount of biomass except in the last season, despite the soil had been managed without herbs for previous years before the beginning of the experiment.

In field 1, BRA was the species that provided the highest amount of C. However, only above-ground biomass was considered to calculate C input. The root system of legumes is smaller than in crucifers and grasses (Alcántara et al. 2009; Ola et al. 2015). The below-ground biomass means an extra C input that has not been taken into account in this study, but it could also affect the increment of SOC, especially in crucifers due to the taproot system (De Baets et al. 2011).

The C sequestration during the four-year study period was significant for BRA at 0–5 cm depth regarding the other groundcovers. BRA showed the most favourable results, increasing more SOC in the surface than the other species. Nevertheless, at 0–20 depth, there were no significant differences between other groundcovers in field 1 (Fig. 20.3).

In field 2, leguminous plants provided less SOC increment than those groundcovers in field 1. The SV2 had little C input to improve SOC at 20 cm in the soil profile. The tillage labour carried out at sowing every year enhanced C emissions and the low biomass reached by SV2 in both management was not enough to improve the SOC in this treatment along the study period. Besides, the tillage performed in the field at the beginning of every season led to a decrease in C stock. The VVI had the highest C sequestration rate without incorporation of residues in field 2. When residues were incorporated, VSA obtained the highest C fixation of this field with 4.85 Mg C ha^{-1} (Fig. 20.4). In this case C input of VSA under M+I system was not as significant as VVI in the M system, but the residue incorporation increased the microbial activity at depth.

At the beginning of the experiments, the initial content of SOC was higher in field 2 than in field 1, significantly affected the stock rate in each experimental field (Blanco-Canqui et al. 2015). The legumes did not reach such an excellent C sequestration rate as the grass and crucifers. The clay content is another soil property of high values in field 1. The soil capacity to accumulate soil C is correlated with the

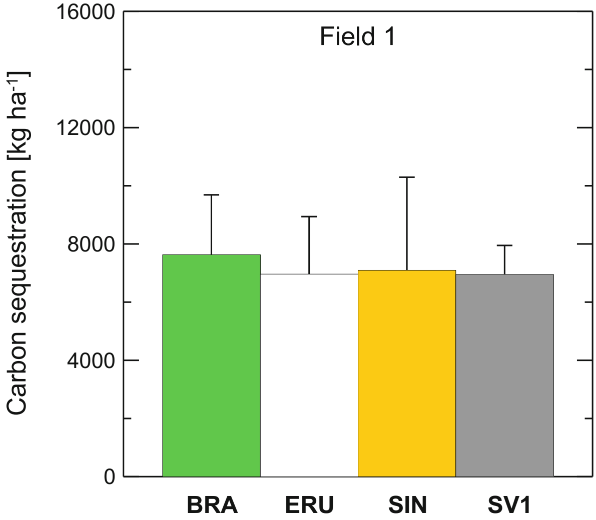

Fig. 20.3 Carbon sequestration through groundcovers of field 1 in 4 seasons at 0–20 cm depth. Error lines represent the standard error. BRA *Brachypodium distachyon*, ERU *Eruca vesicaria*, SIN *Sinapis alba*, *SV1* spontaneous vegetation (field 1)

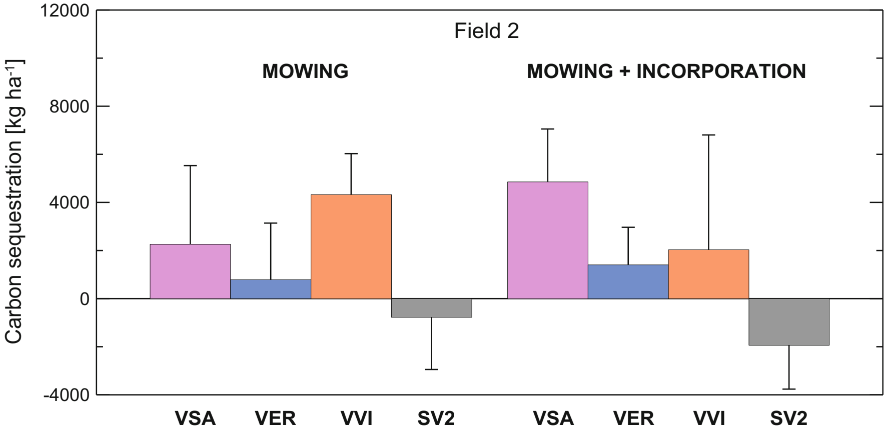

Fig. 20.4 Carbon sequestration through groundcovers in field 2 in 4 seasons at 0–20 cm depth. Error lines represent the standard error. VSA *Vicia sativa*, VER *Vicia ervilia*, VVI *Vicia villosa*, *SV2* spontaneous vegetation (field 2)

clay content (Blanco-Canqui et al. 2015; Poeplau et al. 2017; Iranmanesh and Sadeghi 2019). In field 1, the SOC at origin was mediocre, and clay content was quite high, i.e. nearly 50% (Table 20.3), while in field 2 it was about 12–15% (Table 20.4). Besides, larger-sized pores such as sandy soils might allow the flux of more air during dry periods that oxidises OM. The CEC of the soil is a soil parameter

Table 20.7 Annual C sequestration rate in the first 20 cm of soil during the 4-year experiment

Field 1	C seques. rate (Mg ha^{-1} $year^{-1}$)	Field 2 (M)	C seques. rate (Mg ha^{-1} $year^{-1}$)	Field 2 (M +1)	C seques. rate (Mg ha^{-1} $year^{-1}$)
BRA	1.91	VSA	0.57	VSA	1.21
ERU	1.74	VER	0.20	VER	0.35
SIN	1.77	VVI	1.08	VVI	0.51
SV1	1.74	SV2	-0.19	SV2	-0.48

BRA *Brachypodium distachyon*, ERU *Eruca vesicaria*, SIN *Sinapis alba*, *SV1* spontaneous vegetation (field 1), *SV2* spontaneous vegetation (field 2)

related to the capacity of the soil to improve fertility status. In field 1, the CEC of the soil was higher than in field 2.

The annual rates of C sequestration at 20 cm depth during four seasons are shown in Table 20.7. The annual averages of C fixation in field 1 ranged between 1.74 and 1.79 Mg C ha^{-1} $year^{-1}$. The legumes in field 2 reached lower values ranged between 0.20 and 1.21 Mg C ha^{-1} $year^{-1}$, except SV2 that lost SOC during the study period. In addition to the C emissions produced during tillage at sowing, the lower biomass produced by SV2 narrowed down the C input provided by groundcovers, which limited the increase of soil C. Moreover, the limited amount of residues at the end of the decomposition period increases the risk of erosion and C loss through sediments.

It must be pointed out that the figures indicated here refer to a ton of C per hectare of the surface covered by the specific groundcover. In field 1, groundcovers had a width of 4 m, being the inter-row of 8 m; therefore, the C sequestration would be calculated for half of the olive grove. In the case of field 2, the inter-row width was 6 m, and the width covered by groundcovers was 3.5 m, in other words, 58% of olive grove area would be fixing the measured C rate if extrapolation was made to the whole crop plot.

The results are following the meta-analysis carried out by González-Sánchez et al. (2012), who reported an average C sequestration rate of 1.59 Mg C ha^{-1} $year^{-1}$ comparing it to tillage in woody crops. In the current study, data are also in agreement with Smith et al. (2008) who estimated an annual C sequestration rate between 0.42 and 1.31% with the incorporation of the crop residues and 0.73% with the no-tillage system in annual crops. Aguilera et al. (2013) reported a lower sequestration rate by use of cover crops (≈0.25 Mg C ha^{-1} $year^{-1}$) but indicated 1.11 Mg C ha^{-1} $year^{-1}$ when OM inputs and conservation practices are simultaneously applied, in a meta-analysis of Mediterranean climate soils. Likewise, Vicente-Vicente et al. (2016), in a meta-analysis of C sequestration performed in woody crops, obtained a rate of 1.1 Mg C ha^{-1} $year^{-1}$ through groundcovers in the olive grove.

Researches usually found the depletion in soil C stock when the soil was managed by using the conventional method of tillage. The C loss depends on slope, type of soil and meteorological conditions. Márquez-García et al. (2013) conducted a study in five rainfed olive orchards where groundcovers were compared with conventional tillage and obtained annual SOC losses of −2 Mg C ha^{-1} $year^{-1}$ in one of the fields. The results showed an average fixation of 12.3 Mg CO_2 ha^{-1} $year^{-1}$ compared to tillage for the five fields. The groundcovers were controlled differently in each field

Table 20.8 Amounts of CO_2 fixed annually in the first 20 cm of soil through the use of groundcovers during the 4-year experiment

Field 1	Annual CO_2 fixed (Mg ha^{-1} $year^{-1}$)	Field 2 (M)	Annual CO_2 fixed (Mg ha^{-1} $year^{-1}$)	Field 2 (M +1)	Annual CO_2 fixed (Mg ha^{-1} $year^{-1}$)
BRA	7.00	VSA	2.08	VSA	4.45
ERU	6.38	VER	0.72	VER	1.29
SIN	6.51	VVI	3.97	VVI	1.87
SV1	6.38	SV2	−0.71	SV2	−1.78

BRA *Brachypodium distachyon*, ERU *Eruca vesicaria*, SIN *Sinapis alba*, *SV1* spontaneous vegetation (field 1)

via mechanical mowing, mechanical mowing and tillage, chemical mowing spreading herbicide and control by grazing. Moreover, the annual average of biomass was provided in order to estimate C input, giving generally lower values than presented in this study.

The obtained annual C sequestration rates imply the fixation of atmospheric CO_2 (Table 20.8). The data obtained in the present study are lower than those obtained by Márquez-García et al. (2013). Although in their experiments, soil management systems were compared, provided SOC stock losses in some of their fields managed by tillage, the differences should be higher.

Referring to SOC stock, an issue to consider is the risk of erosion, which leads to loss of OC through eroded sediments. The maintenance of surface vegetative coverage is an effective way to protect the soil against erosion. From an environmental point of view, the selection of a groundcover that maintains the soil protected at that period until the growth of the groundcover in the new season is critical (Rodríguez-Lizana et al. 2018). Table 20.9 shows the percentage of cover at the end of decomposition period when the soil cover level is the lowest for each season, and it coincides with the autumn period of usual massive rainfall events, so the risk of erosion is high. In field 2, the soil coverage after mowing was not assessed using the M+I system; it was very scarce since the residues were incorporated into the soil. The incorporation accelerates the decomposition and the nitrogen availability for olive trees; however, that soil management practice does not provide proper soil protection after mowing.

Legumes did not provide as high soil protection as crucifers and especially as BRA. Grasses species are more recommendable for erosion control as they have a lower decomposition rate than legumes (Repullo-Ruibérriz de Torres et al. 2012). The maximum amount of biomass, C/N ratio and climatic factors are the key factors in the decay process during the decomposition period (Quemada 2004; Duong et al. 2009). The eight studied groundcovers increased the soil cover level between the first and the last season, mainly in field 2, where there were rare herbs before the experiment as bare soil had been the soil management system. The SV2 was the groundcover that provided the lowest soil cover until the fourth season. The soil cover was lower than 30% at the end of the decomposition period. This level is

Table 20.9 Percentage of soil cover (%) provided by residues at the end of decomposition period for each groundcover in every season during the 4-year study period in both fields (only M system was considered in field 2)

	Field 1								Field 2 (M)							
Season	BRA		ERU		SIN		SV1		VSA		VER		VVI		SV2	
1	84.1	a	43.8	b	49.5	b	36.8	b	36.8	a	35.2	a	30.4	a	25.0	a
2	99.3	a	84.8	b	75.4	b	78.1	b	59.4	a	36.0	bc	58.0	ab	28.0	c
3	79.0	a	63.1	a	66.2	a	66.0	a	49.4	a	33.8	b	62.8	a	22.0	B
4	90.0	a	60.6	b	62.0	b	58.9	b	39.0	b	57.0	a	44.2	b	42.2	B

BRA *Brachypodium distachyon*, ERU *Eruca vesicaria*, SIN *Sinapis alba*, *SV* spontaneous vegetation, VSA *Vicia sativa*, VER *Vicia ervilia*, VVI *Vicia villosa*, *SV1* spontaneous vegetation (field 1), *SV2* spontaneous vegetation (field 2)

Different letters indicate significant differences between groundcovers within a field according to the least significant differences (LSD) test ($p \leq 0.05$)

established as a minimum threshold to keep the soil slightly protected from erosive events (González-Sánchez et al. 2015).

20.3.2.3 Experimental Field 3: Pruning Remains Mulch and Spontaneous Vegetation

The experiment was conducted throughout four agricultural seasons in an organic olive grove located in the IFAPA (Andalusia Research Centre) 'Alameda del Obispo' Experimental Station. The coordinates are 37°51′38″N and 4°47′51″W, with an elevation of 117 m above sea level, and it is quite flat (1.7% slope). The organic olive grove has 'Picual' olive trees cultivar, which are 40 years old and a plantation pattern of 8×8 m^2. The physicochemical characteristics of the soil of the experimental field are shown in Table 20.10.

In order to conduct the study, ten olive trees on the farm were pruned and the obtained remains per tree were weighed considering only remains with a diameter $\leq$8 cm in size. The average of pruning materials per tree was 42.3 kg (wet weight). The pruning materials were shredded and spread on a 2 m wide strip, which is a usual size for shredder machine. The pruning materials dose was determined as the ratio of the quantity of pruning materials and the associated surface per tree. This was calculated as the strip width (2 m) and the distance between two olive trees (8 m) [42.3/(2 × 8 m^2) = 2.65 kg m^{-2}]. This dose was established as the first treatment (PR1). An ordinary operation in commercial farms is the application of the pruning materials from two rows on the central inter-row, reducing the number of inter-rows by half (Moreno-García et al. 2018). In this way, the dose of pruning remains would be double (5.30 kg m^{-2}) (PR2). These two pruning remains amounts were applied on soil surface once and left for decomposing during four growing seasons.

The two treatments of pruning remain were compared with a control of spontaneous vegetation that grew naturally in the area (SV3). The main identified species were *Bromus madritensis*, *Bromus hodeaceus*, *Avena barbata*, *Hordeum leporinum*, *Medicago sativa*, *Convolvulus arvensis*, *Cyperus rotundus* and *Crepis vesicaria*. The soil management before and during the study period consisted of controlling

Table 20.10 Physicochemical characteristics of the soil of experimental field 3

Depth (cm)	pH (H_2O)	pH ($CaCl_2$)	EC (dS m^{-1})	$CaCO_3$ (%)	Sand (%)	Silt (%)	Clay (%)	Textural class
0–20	8.6	7.8	0.1	16.4	41.6	40.6	17.8	Loam
20–40	8.6	7.8	0.1	20.4	44.6	37.6	17.9	Loam
40–60	8.8	7.9	0.1	20.9	44.9	37.5	17.7	Loam

Depth (cm)	OM (%)	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	CEC (mol$_c$ kg^{-1})
0–20	1.9	8.0	1.1	18.4	402.6	0.20
20–40	1.3	5.8	1.4	14.1	303.6	0.19
40–60	1.0	8.3	1.6	12.8	205.0	0.17

EC electrical conductivity, *OM* organic matter, NO_3^- nitrate, NH_4^+ ammonium, *P* available phosphorus, *K* exchangeable potassium, *CEC* cation exchange capacity herbs with two mechanical mowings per year. Since this is an organic olive grove, herbicides were applied neither in the inter-row nor under the canopy.

Similarly, to the other fields, the evaluation of the decomposition of the pruning materials, the C release that it entails, soil cover and C sequestration were conducted during four growing seasons. Table 20.11 shows the amount of decomposed biomass and released C during each season as well as the percentage of the C applied at the beginning that remained at the end of every season. The decomposition pattern of pruning remains during four years differs from annual decay of an herbaceous groundcover. During the first growing season, more than 50% was decomposed; however, the rest of the pruning remains degradation was carried out more slowly. In fact, some authors fit the biomass decomposition data to a double exponential model with a higher decay rate at the beginning of the experiment and a lower rate fitted later, representing the recalcitrant components of the residues (Moreno-García et al. 2018).

In this field, spontaneous vegetation was quite abundant since the soil had not been tilled for a long time. Moreover, weeds were not able to be controlled by herbicide as it is an organic olive grove. However, accumulated remains on the surface created a layer isolating the soil that limited its decomposition. Despite the high amount of produced biomass, little biomass was degraded, and carbon release was smaller than that released in other treatments in fields 1 and 2.

The application of significant amounts of pruning remains had an initial herbicidal effect. Nevertheless, as long as remains are degrading the possibilities for appearing spontaneous flora in the pruning remains subplots increase. It might imply an extra C input that has not been measured in this research since only biomass from pruning remains has been assessed and shown in Table 20.11.

The treatments with pruning remains enhanced the stock of SOC. Figure 20.5 shows the C sequestration obtained during four growing seasons at 0–20 cm depth. The sequestration rates for pruning remains were too high compared with those obtained by herbaceous groundcover such as SV3 (Table 20.12). Significant differences were found between treatments with pruning remains and SV3. PR1 provided a sequestration rate of 3.53 and PR2 of 4.84. These values are quite higher than those indicated in other research in the Mediterranean area. It must be taken into account that pruning remains were applied just in 2 m strip and the doses of 2.65 and 5.30 kg m^{-2} mean a high C input in this strip. If pruning remains had been spread on the whole olive grove surface the dose of PR1 would have been 0.66 kg m^{-2} (wet weight), considering the moisture in residue, that means 0.39 kg m^{-2} of dry matter. This value was similar to that observed for a biennial pruning by Velázquez-Martí et al. (2011).

The obtained sequestration rates do not differ widely from those observed in earlier studies. Nieto et al. (2010) obtained an increase of 1.88 and 2.33 Mg C ha^{-1} $year^{-1}$ with olive pruning remains in both olive groves. Romanyà et al. (2000) registered an annual fixation rate of 1.4 Mg C ha^{-1} $year^{-1}$ for a vineyard in the Mediterranean area.

Regarding soil protection, pruning remains acting as mulch has proven to be an efficient tool. Its slow decomposition allows maintaining the soil cover quite high

Table 20.11 Amount of biomass of pruning remains applied at origin and C content (kg ha^{-1} dry matter), decomposed biomass, released C using pruning remains and SV3 (kg ha^{-1} dry matter) and percentage of remaining C (%) using pruning remains in every season during the 4-year study period

	PR1			PR2				
Applied	Biomass	C content	%C Remain.	Residue	C content	%C Remain.		
At origin	15,672.0	7310.5	100	31,344.1	14,621.0	100	SV3	
Season	Biomass decomp.	C release	%C remain.	Biomass decomp.	C release	%C remain.	Biomass decomp.	C release
1	7925.5	4295.7	41.2	13928.9	7725.0	47.2	2252.3	925.8
2	2326.0	983.9	27.8	8705.4	3422.8	23.8	2338.7	810.0
3	2921.7	1257.0	10.6	4745.0	2319.8	7.9	3042.1	1058.3
4	1001.6	412.5	4.9	558.1	160.1	6.8	3461.3	1411.0
Total	14,174.9	6949.1		27,937.5	13,627.7		11,094.4	4205.1

PR1 pruning remains mulch (dose 1), *PR2* pruning remains mulch (dose 2)

Fig. 20.5 Carbon sequestration through pruning remains mulches and spontaneous vegetation in field 3 for four seasons at 0–20 cm depth. Error lines represent the standard error. Different letters indicate significant differences according to LSD test ($p \leq 0.05$). *PR1* pruning remains mulch (dose 1), *PR2* pruning remains mulch (dose 2), *SV3* spontaneous vegetation (field 3)

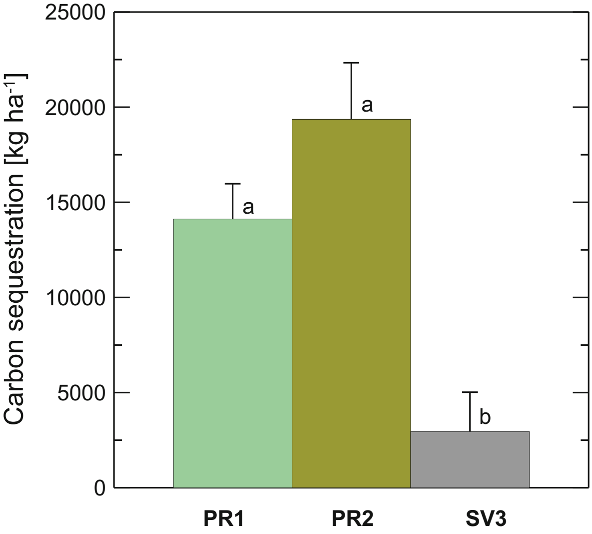

Table 20.12 Annual C sequestration rate in the first 20 cm of soil during the 4-year experiment and amount of CO_2 fixed annually

Field 3	ΔSOC (kg ha^{-1})	C sequestration rate (Mg ha^{-1} year^{-1})	Annual fixed CO_2 (Mg ha^{-1} year^{-1})
PR1	14,125.76	3.53	12.95
PR2	19,367.16	4.84	17.75
SV3	2956.50	0.74	2.71

PR1 pruning remains mulch (dose 1), *PR2* pruning remains mulch (dose 2), *SV3* spontaneous vegetation (field 3)

until the fourth season. However, in the last season, the pruning remains of PR1 only had 22% of soil cover that is under the threshold of 30%. By contrast, PR2 provided 42% of soil cover at the end of the fourth season. In the case of pruning remains, spontaneous vegetation may appear while those are decomposing so that it would provide soil protection. This situation occurred in field 3, where SV3 maintained an excellent soil cover during the whole season. Also, a biennial pruning can be expected in the olive grove; thus, in four years, there should be a new application of pruning remains on the soil.

The ratio C sequestration per C input through biomass differs for the different treatments studied. In field 1, this ratio is 0.7 for BRA, but it is higher for ERU, SIN and SV1 due to the C input from root biomass, which has not been considered. The ratios in field 2 ranged between 0.14 and 0.60, which are similar to those found by Aguilera et al. (2013). In field 3, this ratio was 0.70 for SV3 but much higher for pruning remains treatments since spontaneous flora appeared in PR1 and PR2 subplots while remains that were degraded were not taken into account for the C input. In any case, it seems that as OM is improved, there are synergy processes.

Microorganism might be encouraged by SOC increments at surface and depth. Vicente-Vicente et al. (2016) also found ratios higher than 1 in their meta-analysis. All groundcovers used in this research except SV2 fulfilled thoroughly the goal proposed by '4perMille' initiative about annual C sequestration rate (Minasny et al. 2017).

20.4 Conclusions

All types of groundcover increased carbon (C) sequestration except spontaneous vegetation field 2 (SV2) where biomass was scarce. Field 1 with soil having higher clay content obtained better results in soil organic carbon (SOC) than field 2 with similar C input supplied. The use of legumes as groundcover allows obtaining agronomic and environmental benefits which are an opportunity for organic farming. Although legumes are not the most recommended type of groundcover to protect the soil, *Vicia sativa* and *Vicia villosa* provided good soil cover, in the mowing system, and a medium-high C sequestration rate in both soil management. Furthermore, the nitrogen supplied by leguminous plants entails savings in fertilisation, which could reduce the nitrous oxide emissions that is one of the most important greenhouse gases. Carbon sequestration was higher in organic amendments such as pruning remains mulches due to the high doses applied. However, the strip width where they are applied must be taken into account because the improved fertility area is not as high as the area occupied by living groundcovers. Regarding soil cover, the grass used in field 1, *Brachypodium distachyon*, kept the highest level during the four-year study period, but pruning remains mulches maintain constant soil protection during the first seasons. The use of any groundcover is highly recommendable because of their contribution to protect the soil and mitigate climate change through SOC sequestration. The treatment in which farmers have taken parts such as seeded groundcover or pruning remains mulches provided better results than spontaneous vegetation in all experimental fields. Even though spontaneous vegetation is the most popular option used by farmers to cover the soil of their olive groves, the results of this study reveal that other types of groundcovers can be more beneficial for fixing into the soil part of the atmospheric C sequestered in plant remains and for providing higher and long-lasting protection.

20.5 Future Perspectives

Given the good results in carbon sequestration obtained through groundcovers, it is expected that policymakers focus the aids on this good agricultural practice environmentally sustainable. Future research should focus on the use of different types of groundcover. For instance, mixes of species from different families, such as gramineous and leguminous plant, mixes of multiples species or a mix of pruning residues with spontaneous vegetation. Furthermore, groundcovers rotation after a determinate number of seasons could help to reduce some problems caused by the continued use of the same type of groundcover such as flora inversion, soil compaction or pest risk. In addition, the type of chipping machines and mower technology will adapt to the olive orchard conditions. Likewise, treatment machines for chemical weeding and technology development in herbicides can help to foster the use of groundcovers in the inter-row of olive orchards and other permanent crops. On this aspect, herbicide technology should focus on reducing the use of herbicide, based on precision agriculture. In order to reduce inputs for groundcover management, development of self-seeding species such as *Brachypodium distachyon* is recommendable. It would be useful to protect the soil more permanently, reduce seeding operation and save seed costs. Political agricultural programmes should boost soil research with the main emphasis on agricultural soil conservation and its contribution to climate change mitigation and adaptation. The scope should be focused on the possibility of using soil management practices to increase soil organic matter and then to use soils to store carbon favouring CO_2 sequestration.

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References

Aguilera E, Lassaletta L, Gattinger A, Gimeno BS (2013) Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agric Ecosyst Environ 168:25–36. https://doi.org/10.1016/jagee201302003

Alcántara C, Sánchez S, Pujadas A, Saavedra M (2009) Brassica species as winter cover crops. Sustainable agricultural systems in southern Spain. J Sustain Agric 33:619–635

Alcántara C, Pujadas A, Saavedra M (2011) Management of cruciferous cover crops by mowing for soil and water conservation in southern Spain. Agric Water Manag 98:1071–1080

Alonso-Ayuso M, Gabriel JL, Quemada M (2014) The kill date as a management tool for cover cropping success. PLoS ONE 9:0109587

Ávila E, Herrera A, Tezara W (2014) Contribution of stem CO2 fixation to whole-plant carbon balance in nonsucculent species. Photosynthetica 52:3–15

Barranco D, Fernández-Escobar R, Rallo L (2008) El Cultivo del Olivo, 6th edn. Junta de Andalucía, Sevilla

Blanco-Canqui H, Shaver TM, Lindquist JL, Shapiro CA, Elmore RW, Francis CA, Hergert GW (2015) Cover crops and ecosystem services: insights from studies in temperate soils. Agron J 107:2449–2474

Carbonell-Bojollo R, González-Sánchez EJ, Veróz-González O, Ordóñez-Fernández R (2011) Soil management systems and short-term CO2 emissions in a clayey soil in southern Spain. Sci Total Environ 409:2929–2935

Carbonell-Bojollo R, González-Sánchez EJ, Repullo-Ruibérriz de Torres M, Ordóñez-Fernández R, Domínguez-Giménez J, Basch G (2015) Soil organic carbón fractions under conventional and no-till management in a long-term study in southern Spain. Soil Res 53:113–124

Carbonell-Bojollo R, Veroz-González O, Ordóñez-Fernández R, Moreno-García M, Basch G, Kassam A, Repullo-Ruibérriz de Torres M, González-Sánchez EJ (2019) The effect of conservation agriculture and environmental factors on CO2 emissions in a rainfed crop rotation. Sustainability 11:3955

Ciscar JC, Iglesias A, Feyen L, Szabó L, Van Regemorter D, Amelung B, Nicholls R, Watkiss P, Christensen OB, Dankers R, Garrote L, Goodess CM, Hunt A, Moreno A, Richards J, Soria A (2011) Physical and economic consequences of climate change in Europe. Proc Natl Acad Sci U S A 108:2678–2683

De Baet S, Poesen J, Reubens B, Muys B, De Baerdemaeker J, Meersmans J (2009) Methodological framework to select plant species for controlling rill and gully erosion: application to a Mediterranean ecosystem. Earth Surf Process Landf 34:1374–1392

De Baets S, Poesen J, Meersmans J, Serlet L (2011) Cover crops and their erosion-reducing effects during concentrated flow erosion. Catena 85:237–244

Donatelli M, Srivastava AK, Duveiller G, Niemeyer S (2012) Estimating impact assessment and adaptation strategies under climate change scenarios for crops at EU27 scale. International Environmental Modelling and Software Society (iEMSs) Secretariat, Manno, pp 404–411

Duong TT, Baumann K, Marschner P (2009) Frequent addition of wheat straw residues to soil enhances carbon mineralization rate. Soil Biol Biochem 41:1475–1482

Durán-Zuazo VH, Rodríguez-Pleguezuelo CR, Arroyo-Panadero L, Martínez-Raya A, Francia-Martínez JR, Cárceles-Rodríguez B (2009) Soil conservation measures in rainfed olive orchards in South-Eastern Spain: impacts of plant strips on soil water dynamics. Pedosphere 19:453–464

European Commission (2009) White paper. Adapting to climate change: towards a European framework for action. Commission of the European Communities, Brussels

EUROSTAT (2016) Agriculture, forestry and fishery statistics. European Union, Luxemburg, p 206

Fernández-Romero ML, Lozano-García B, Parras-Alcantara L, Collins CD, Clark JM (2014) Effects of land management on different forms of soil carbón in olive groves in Mediterranean areas. Land Degrad Dev 27:1186–1195

Francia JR, Durán VH, Martínez A (2006) Environmental impact from mountainous olive orchards under different soil-management systems (SE Spain). Sci Total Environ 358:46–60

Franklin D, Truman C, Potter T, Bosch D, Strickland T, Bednarz D (2007) Nitrogen and phosphorus runoff losses from variable and constant intensity rainfall simulations on loamy sand under conventional and strip tillage systems. J Environ Qual 36:846–854

Franzluebbers AJ (2002) Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res 66:95–106

García-Ruiz JM, López-Moreno JI, Vicente-Serrano SM, Lasanta-Martínez T, Baguería S (2011) Mediterranean water resources in a global change scenario. Earth Sci Rev 105:121–139

Gómez JA, Giráldez JV, Fereres E (2005) Water erosion in olive orchards in Andalusia (Southern Spain): a review. Geophys Res Abstr 7:8406

Gómez JA, Sobrinho TA, Giráldez JV, Fereres E (2009) Soil management effects on runoff erosion and soil properties in an olive grove of Southern Spain. Soil Tillage Res 102:5–13

Gómez JA, Llewellyn C, Bash G, Sutton B, Dyson JS, Jones CA (2011) The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. Soil Use Manag 27:502–514

Gómez-Limón JA, Arriaza M (2011) Evaluación de la Sostenibilidad de las Explotaciones de Olivar en Andalucía Analistas Económicos de Andalucía. Málaga, España

González-Sánchez EJ, Gómez-Ariza M, Rodríguez-Lizana A (2007) El sistema de cubierta en el olivar andaluz Tipos y manejo. In: Rodríguez-Lizana A, Ordóñez-Fernández R, Gil-Ribes J (eds) Cubiertas vegetales en olivar Consejería de Agricultura y Pesca. Junta de Andalucía, Sevilla

González-Sánchez EJ, Ordóñez-Fernández R, Carbonell-Bojollo R, Veroz-González O, Gil-Ribes JA (2012) Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. Soil Tillage Res 122:52–60

González-Sánchez EJ, Veroz-González O, Blanco-Roldán GL, Márquez-García F, Carbonell-Bojollo R (2015) A renewed view of conservation agriculture and its evolution over the last decade in Spain. Soil Tillage Res 146:204–212

Gupta A, Kumar A (2018) Climate resilient agro-technologies for enhanced crop and water productivity under water deficit agro-ecologies. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 339–356

Guzmán Casado GI, Alonso Mielgo AM (2001) El uso de abonos verdes en agricultura ecológica Boletín n° 47/01 Ed CAAE, Sevilla, España

Hernanz JL, Girón VS, Ceriesola C (1995) Long-term energy use and economic evaluation of three tillage systems for cereal and legume production in central Spain. Soil Tillage Res 35:183–198

Iglesias A, Garrote L, Diz A, Schlickenrieder J, Moneo M (2012) Water and people: assessing policy priorities for climate change adaptation in the Mediterranean. In: Navarra A, Tubiana L (eds) Regional assessment of climate change in the Mediterranean. Springer, Dordrecht, pp 201–233

Iranmanesh M, Sadeghi H (2019) Effects of soil texture and nitrogen on ability of carbon sequestration in different organs of two Tamarix species as a good choice for carbon stock in dry lands. Ecol Eng 139:105577

Kang Y, Khan S, Ma X (2009) Climate change impacts on crop yield, crop water productivity and food security – a review. Prog Nat Sci 19:1665–1674

Kassam A, Friedrich T, Derpsch R, Lahmar R, Mrabet R, Basch G, González-Sánchez EJ, Serraj R (2012) Conservation agriculture in the dry Mediterranean climate. Field Crop Res 132:7–17

Kaye JP, Quemada M (2017) Using cover crops to mitigate and adapt to climate change. A review. Agron Sustain Dev 37:4

Kimble JM, Heath LS, Birdsey RA, Lal R (2003) The potential of US forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press, New York

Kovats RS, Valentini R, Bouwer LM, Georgopoulou E, Jacob D, Martin E, Rounsevell M, Soussana JF (2014) Climate change 2014: impacts, adaptation, and vulnerability Part B: regional aspects Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 1267–1326

Krutz LJ, Locke MA, Steinriede RW (2009) Interactions of tillage and cover crop on water, sediment, and pre-emergence herbicide loss in glyphosate-resistant cotton: implications for the control of glyphosate-resistant weed biotypes. J Environ Qual 38:1240–1247

Kumar S, Sheoran S, Kakraliya SK, Kumar P, Meena RS (2016) Drought: a challenge for Indian farmers in context to climate change and variability. Prog Res 11:6243–6246

Kumar S, Meena RS, Jakhar SR, Jangir CK, Gupta A, Meena BL (2019) Adaptation strategies for enhancing agricultural and environmental sustainability under current climate. In: Meena RS (ed) Sustainable agriculture. Scientific Publisher, Jodhpur, pp 226–274

Kumar S, Meena RS, Datta R, Verma SK, Yadav GS, Pradhan G, Molaei A, Mustafizur Rahman GKM, Mashuk HA (2020) Legumes for carbon and nitrogen cycling: an organic approach. In: Datta R, Meena RS, Pathan SI, Ceccherini MT (eds) Carbon and nitrogen cycling in soil. Springer, Cham, pp 337–375

Lal R (2003) Soil erosion and the global carbon budget. Environ Int 29:437–450

Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 132:1–22

Lal R (2014) Societal value of soil carbon. J Soil Water Conserv 69:186–192

MAPA (2018) Encuesta sobre superficies y rendimientos de cultivos (ESYRCE) Resultados 2018 Subsecretaría de Agricultura, Pesca y Alimentación Subdirección general de Análisis, Coordinación y Estadística, Gobierno de España

Márquez-García F (2017) Capacity of groundcovers to mitigate and adapt to climate change in olive groves under semiarid conditions. PhD thesis, Univ Córdoba

Márquez-García F, González-Sánchez EJ, Castro-García S, Ordóñez-Fernández R (2013) Improvement of soil carbon sink by cover crops in olive orchards under semiarid conditions Influence of the type of soil and weed. Span J Agric Res 11:335–346

Meena RS, Bohra JS, Singh SP, Meena VS, Verma JP, Verma SK, Sihag SK (2016) Towards the prime response of manure to enhance nutrient use efficiency and soil sustainability a current need: a book review. J Clean Prod 112(1):1258–1260

Meena RS, Gogoi N, Kumar S (2017) Alarming issues on agricultural crop production and environmental stresses. J Clean Prod 142:3357–3359

Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, Sharma MP, Yadav GS, Jhariya MK, Jangir CK, Pathan SI, Dokulilova T, Pecina V, Marfo TD (2020a) Impact of agrochemicals on soil microbiota and management: a review. Land 9(34):1–22

Meena RS, Lal R, Yadav GS (2020b) Long term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in Central Ohio, USA. Geoderma 363:1141164

Minasny D, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, Chaplot V, Chen Z-S, Cheng K, Das BS, Field DJ, Gimona A, Hedley CB, Hong SY, Mandal B, Marchant BP, Martin M, McConkey BG, Mulder VL, O'Rourke S, Richer-de-Forges AC, Odeh I, Padarian J, Paustian K, Pan G, Poggio L, Savin I, Stolbovoy V, Stockman U, Sulaeman Y, Sulaeman C-C, Vagen T-G, van Wesemael B, Winowiecki L (2017) Soil carbon 4 per mille. Geoderma 292:59–86

Moreno M, Garcia S, Cañizares R, Castro J, Benítez E (2009) Rainfed olive farming in south-eastern Spain: long-term effect of soil management on biological indicators of soil quality. Agric Ecosyst Environ 131:333–339

Moreno-García M, de Repullo-Ruibérriz Torres MA, Carbonell-Bojollo RM, Ordóñez-Fernández R (2018) Management of pruning residues for soil protection in olive orchards. Land Degrad Dev 29:2975–2984

Nassi Di Nasso N, Bosco S, Di Bene C, Coli A, Mazzoncini M, Bonari E (2011) Energy efficiency in long-term Mediterranean cropping systems with different management intensities. Energy 36:1924–1930

Newton AC, Johnson SN, Gregory PJ (2011) Implications of climate change for diseases, crop yields and food security. Euphytica 179:3–18

Nieto OM, Castro J, Fernández E, Smith P (2010) Simulation of soil organic carbon stock in a Mediterranean Olive grove under different soil-management systems using Roth C model. Soil Use Manag 26:118–125

Oades JM (1993) The role of biology in the formation, stabilization and degradation of soil structure. Geoderma 56:377–400

Ola A, Dodd IC, Quinton JN (2015) Can we manipulate root system architecture to control soil erosion? Soil 1:603–612

Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96–112

Ordóñez-Fernández R, Rodríguez-Lizana A, Espejo AJ, González P, Saavedra M (2007a) Soil and available phosphorus losses in ecological olive groves. Eur J Agron 27:144–153

Ordóñez-Fernández R, Rodríguez-Lizana A, Carbonell R, González P, Perea F (2007b) Dynamics of residue decomposition in the field in a dryland rotation under Mediterranean climate conditions in southern Spain. Nutr. Cycl Agroecosyst 79:243–253

Ordóñez-Fernández R, de Repullo-Ruibérriz Torres MA, Márquez-García J, Moreno-García M, Carbonell-Bojollo R (2018) Legumes used as cover crops to reduce fertilisation problems improving soil nitrate in an organic orchard. Eur J Agron 95:1–13

Paul E, Follet SW, Leavitt A, Halvorson GA, Peterson GA, Lyon DJ (1997) Radio carbon dating for determination of soil organic carbon pool sizes and dynamics. Soil Sci Soc Am J 61:1058–1067

Peterhansel C, Offermann S (2012) Re-engineering of carbon fixation in plants- challenges for plant biotechnology to improve yields in a high-CO2 world. Curr Opin Biotechnol 23:204–208

Poeplau C, Reiter L, Berti A, Kätterer T (2017) Qualitative response of soil carbon to 40 years of crop residue incorporation under contrasting nitrogen fertilisation regimes. Soil Res 55:1–9

Quemada M (2004) Predicting crop residue decomposition using moisture adjusted scales. Nutr Cycl Agroecosyst 70:283–291

Quemada M, Baranski M, Nobel-de Lange MNJ, Vallejo A, Cooper JM (2013) Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. Agric Ecosyst Environ 174:1–10

Rani K, Sharma P, Kumar S, Wati L, Kumar R, Gurjar DS, Kumar D, Kumar R (2019) Legumes for sustainable soil and crop management. In: Meena RS, Kumar S, Bohra JS, Jat ML (eds) Sustainable management of soil and environment. Springer, Cham, pp 193–215

Repullo-Ruibérriz de Torres MA, Carbonell-Bojollo R, Alcántara-Braña C, Rodríguez-Lizana A, Ordóñez-Fernández R (2012) Carbon sequestration potential of residues of different types of cover crops in olive groves under Mediterranean climate. Span J Agric Res 10:649–661

Repullo-Ruibérriz de Torres MA, Ordóñez-Fernández R, Giráldez JV, Márquez-García J, Laguna A, Carbonell-Bojollo R (2018) Efficiency of four different seeded plants and native vegetation as cover crops in the control of soil and carbon losses by water erosion in olive orchards. Land Degrad Dev 29:2278–2290

Robertson FA, Thorburn PJ (2007) Decomposition of sugarcane harvest residue in different climatic zones. Aust J Soil Res 45:1–11

Roca LF, Moral J, Trapero C, Blanco-López MÁ, López-Escudero FJ (2016) Effect of inoculum density on verticillium wilt incidence in commercial olive orchards. J Phytopathol 164:61–64

Rodríguez-Lizana A, Repullo-Ruibérriz de Torres MA, Carbonell-Bojollo R, Alcántara C, Ordóñez-Fernández R (2018) Brachypodium distachyon, Sinapis alba, and controlled spontaneous vegetation as groundcovers: Soil protection and modeling decomposition. Agric Ecosyst Environ 265:62–72

Rogaard L, de Porcellinis AJ, Jacobsen JH (2012) Bioengineering of carbón fixation, biofuels, and biochemicals in cyanobacteria and plants. J Biotechnol 162:134–147

Romanyà J, Cortina J, Fallon P, Colleman K, Smith P (2000) Modelling changes in soil organic matter after planting fast-growing Pinus radiata on Mediterranean agricultural soils. Eur J Soil Sci 51:627–641

Saavedra M, Pastor M (2002) Sistemas de cultivo en olivar Manejo de malas hierbas y herbicidas. Editorial Agrícola Española, Madrid

Shetty KG, Subbarao KV, Huisman OC, Hubbard JC (2000) Mechanism of broccoli mediated verticillium wilt reduction in cauliflower. Phytopathology 90:305–310

Smith P (2007) Agriculture climate change 2007: mitigation contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 497–540

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O, Howden M, McAllister T, Pan G, Romanenkov V, Schneider U, Towprayoon S, Wattenbach M, Smith J (2008) Greenhouse gas mitigation in agriculture. Philos Trans R Soc London 363:789–813

Soil Survey Staff (2014) Keys to soil taxonomy, 12th edn. USDA, Washington DC

Stagnari F, Maggio A, Galieni A, Pisante M (2017) Multiple benefits of legumes for agriculture sustainability: an overview. Chem Biol Technol Agric 4:2

Taguas EV, Moral C, Ayuso JL, Pérez R, Gómez JA (2011) Modeling the spatial distribution of water erosion within a Spanish olive orchard microcatchment using SEED model. Geomorphology 133:47–56

Torn MS, Trumbore SE, Chadwick OA, Vitousek PM, Hendricks DM (1997) Mineral control of soil organic carbon storage and turnover. Nature 389:170–173

Triplet GB, Dick WA (2008) No-tillage crop production: A revolution in agriculture! Agron J 100:153–165

UN (2008) United Nations expert group meeting on population distribution, urbanization, internal migration and development. New York, 21-23 January 2008

UNEP (2012) Greenhouse gases and climate change global environment outlook 3. https://www.uneporg/geo/geo3/english/368htm. Access 11 Nov 2019

Vanwalleghem T, Laguna A, Giráldez JV, Jiménez-Hornero FJ (2010) Applying a simple methodology to assess historical soil erosion in olive orchards. Geomorphology 114:294–302

Velázquez-Martí B, Fernández-González E, López-Cortes I, Salazar-Hernández DM (2011) Quantification of the residual biomass obtained from pruning of trees in Mediterranean olive groves. Biomass Bioenergy 35(7):3208–3217

Vicente-Vicente JL, García-Ruiz R, Francaviglia R, Aguilera E, Smith P (2016) Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: a meta-analysis. Agric Ecosyst Environ 235:204–214

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38

Wolfe D (2000) Summer covers relieve compaction. In: Clark A (ed) Managing cover crop profitably. Sustainable Agriculture Network, Beltsville, p 84