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Input Use Efficiency for Food and Environmental Security

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This book is dedicated to Dr. Gulab Singh Yadav.

Dr. Gulab Singh Yadav was born in a farmer’s family in Bareilly, Uttar Pradesh, India, on July 1, 1982. Dr. Yadav was posted at the Division of Agronomy, ICAR-Indian Agricultural Research Institute in New Delhi. Dr. Yadav received his M.Sc. (Ag.) and Ph.D. from IARI in New Delhi, India, as well as his Post Doctorate Research from the Ohio State University in Columbus, USA. He worked as an Agricultural Research Scientist (ARS) in the ICAR Research Complex for the North-Eastern Hill Region in Tripura, India (2011–2020). Dr. Yadav created revolutionary agronomic approaches to aid India's hill *farmers. In the Eastern Himalayan area, he was a creator in the development of climate-resilient agricultural technology for sustainable agriculture. His resource conservation practises have been widely adopted by India's small and marginal landowners in the Eastern Himalayan area. He received Dr. D.N. Borthakur Award, Swami Sahajanand Saraswati Outstanding Extension Scientist Award, Fakhruddin Ali Ahmed Award for contribution to Farming System Research by ICAR, and many more have been bestowed upon him. As a prolific scientist and writer, he published over 150 peer-reviewed scientific papers, six books, and other works. Dr. Yadav was a visionary and kind guy.*

Preface

The world's population is expected to increase to ~9 billion by 2050, and feeding such a large population from available resources is not an easy task with shrinking resources. Due to the rapid increase in the price of farm inputs, it is critical to achieve high levels of efficiency in their use in order to increase output and profit. To double agricultural revenue, policymakers are focusing on achieving the highest level of efficiency in every resource use, especially in the era of escalating global population under global warming. Over the last few decades, there has been awareness in enhancing the efficiency of usage of applied inputs, since people intervened in natural agroecosystems and services to meet food needs. Farmers are using the higher doses of these inputs for enhancing the yields and their incomes, but at the end they are under a big loss, which might be the reason why farmers quitting agriculture. The irreversible destruction of land, air and water quality, as well as the jeopardization of biodiversity, has all been identified as significant parts of the current agricultural development concept's unsustainable nature. Several textbooks and edited volumes on general soil management and the agricultural environment are already available, but none has been dedicated to improve the use efficiency of different inputs, viz. water, fertilizers, pesticides, insecticides, and weedicides for food and environmental security. This book focuses on the effects of sustainable soil and environmental management on soil-ecosystem functioning, agronomic productivity, and food security, nutrient cycling, recent advances in integrated nutrient management, eco-friendly cultivation, and agricultural practices that improve yields and reduce greenhouse gas (GHG) emissions.

The book has a comprehensive scope of resource management impacts on the long-term viability of soil, agro-ecosystems and for environmental security. Adoption of alternative crop establishment methods is crucial for improving water productivity, soil sustainability and food and nutritional security without sacrificing yield potentials. The goals of this book are to: (1) comprehend the options for 'Input Use Efficiency for Food and Environmental Security' and their significance to long-term sustainability; (2) conserve and improve the use efficiency of different inputs for reducing costs of cultivation which further add to the farmers livelihoods, and (3) comprehend how to reconcile finite natural resource supply with crop demand for nutritional security in an environmentally friendly context. The editors and authors present a roadmap for the long-term development of agricultural systems for food, nutritional and environmental security.

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About the Editors

Rajan Bhatt is working as Senior Soil Scientist at PAU-Regional Research Station, Kapurthala, Punjab, India, and the author or co-author of more than 85 scientific papers, 03 books, 33 book chapters and several extension articles. Dr. Bhatt acquired a B.-Sc. (Agriculture) from Guru Nanak Dev University, Amritsar, Punjab, India, while M.Sc. and Ph.D. (both in Soil Science) degrees from Punjab Agricultural University, Ludhiana, Punjab, India. Dr. Bhatt was awarded >16 awards at the state and national level and reviewed 52 research articles after receiving invitation from high-impact journals. He is handling three projects as PI and two projects as CO-PI. He is an editorial board member for several journals and a life member of numerous societies.

Ram Swaroop Meena is working as an Assistant Professor (S-3) in the Department of Agronomy, I.Ag. Scs., BHU, Varanasi (UP). Dr. Meena has been awarded Raman Research Fellowship by the MHRD, GOI. He has completed his postdoctoral research on soil carbon sequestration under Padma Shari Prof. Rattan Lal, World Food Prize 2020 Laureate, Director, CMASC, Columbus, USA. Dr. Meena has supervised 25 PG and 7 PhD students and has 11 years of research and teaching experience. He is working on three externally funded projects (DST, MHRD, ICAR) with one patent. Dr. Meena has published more than 110 research and review papers with a total impact factor of 230.43 and an H-index of 45 as well as 4 published books at the national level and 17 books at the international level, and contributed 20 chapters in books at the national level and 50 at the international level. Dr. Meena serves as an editor for 12 journals. He has worked as an expert for the school education in NCERT, MHRD, GOI. Dr. Meena has contributed to several agricultural extension activities, trainings, meetings, workshops, etc.

Akbar Hossain is currently working as a Principal Scientist, Soil Science Division, Bangladesh Wheat and Maize Research Institute (BWMRI), Dinajpur 5200, Bangladesh. Dr. Hossain has been awarded Russian Government Research Fellowship for Ph.D. study in Russia. He has completed his postdoctoral research on ‘Isolation, characterization and purification of Rhizobium strain to enrich the productivity of groundnut (*Arachis hypogaea* L.)’ in BCKV, WB, India, through DST-India fellowship. Dr. Hossain has supervised 15 postgraduate students in HSTU, Dinajpur, and BAU, Mymensingh, Bangladesh. He has been working with several international research projects funded by CIMMYT, CSISA, ACIAR, CSIRO-Australia, the University of Queensland, Australia, OCPF-BARI-ICARDA and Tufts University, USA. Dr. Hossain has been working on climate change, plant physiology, defence mechanisms against stress, conservation agriculture, crop modelling, nanotechnology, etc. Dr. Hossain has authored more than 250 national and international journal articles. He has edited two books published by Intech Open, UK.

Input Use Efficiency in Rice–Wheat Cropping Systems to Manage the Footprints for Food and Environmental Security

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Rajan Bhatt, Ram Swaroop Meena, and Akbar Hossain

Abstract

Global population is escalating at a faster rate that could reach to 9 billion up to the 2050, and to feed such a higher population in a sustainable way from the limited resources of land and water is not an easy task. Popular conventional crop establishment techniques among the farmers are energy, water, labor, and capital intensive have higher carbon, water and energy footprints which further led to declined soil health, ground water levels, land and water productivities and higher micronutrient deficiencies. Adverse effects of the overall global warming and their influence on the agricultural production further complicated the situations of achieving food and environmental security in a sustainable manner. All result in reduced yields of the system as a whole. To improve their yields, farmers tend to add more resources, viz., water, fertilizers, and even, pesticides, which instead of helping this further deteriorated the production of higher volumes of greenhouse gases and more edible leaves, causing pollution in both soil and water bodies. Emphasis must be placed on the enhancement of the soil organic matter status to improve soil properties. Moreover, frequent escape of the greenhouse gases, viz., carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) must be checked for mitigating the adverse effects of the climate change to have sustainable

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environmental security and higher use efficiency of the applied inputs. There is also a need to put the problematic soils, viz., salt affected, wastelands, or waterlogged, sandy soils under cultivation by reclaiming them sustainably for having their contribution in the food security. Food security is a must for the global population but in a sustainable manner. Sustainable crop residues management can avoid the open burnings in fields, secure the quality of the environment, and minimize the complications of the global warming. Reducing food loss and wastage helps to reduce the targets of food production and exploitation of the natural resources. Farmers must be educated for reducing the water, energy, and C footprints by improving their use efficiencies (rather to enhance their dose) through different technologies in the most prevalent cropping sequence of the region, viz., minimum tillage, precision land leveling, tensiometer guided irrigations particularly in rice, un-puddled direct rice grains seeding, bed planting, etc. These technologies are also known as Resource Conservation Technologies (RCTs) that depend on soil textural class and agro-climatic conditions. Hence, to serve the purpose of improving the use efficiency of applied inputs, viz., water, fertilizers, pesticides and energy, these RCTs are recommended in the region so as to have global food and environmental security in a sustainable and climate smart way.

Keywords

Input use efficiency · Resource conservation technologies · Food security · Environmental security · Climate change

Abbreviations

CH_4	Methane
CO_2	Carbon dioxide
DSR	Direct seeding of rice
E	Evaporation
ET	Evapotranspiration
LLL	Laser land levelling
MTR	Mechanically transplanted rice
N_2O	Nitrous oxide
PTR	Puddle transplanted system
PTR	Puddled transplanted rice
RCTs	Resource conservation technologies
RWCS	Rice–wheat cropping sequence
SA	South Asia
SMP	Soil matric potential
SPAD	Soil plant analysis development
T	Transpiration
ZT DSR	Zero till direct seeding of rice

ZT MTR	Zero till mechanically transplanted rice
ZT	Zero tillage

1.1 Introduction

Rice–wheat cropping system (RWCS), being practiced in more than 24 million hectares including India and China alone, claims to be the single largest cropping sequence adopted worldwide. In India, the Indo-Gangetic Plain (IGP) extends in the Northwest from Punjab to East in West Bengal (Bhatt et al. 2021; Singh et al. 2005). Further, India (12.3 M ha), Nepal (0.5 M ha), Pakistan (2.2 M ha), and Bangladesh (0.8 M ha) adopt conventional RWCS, major portion of which belongs to IGP (around 85%) (Ladha et al. 2003; Timsina and Connor 2001), and this produces nearly half of food grains of South Asia (Jat et al. 2005). In South Asia, the long-term sustainability of RWCS is in jeopardy now due to prolonged adoption of faulty crop establishment techniques (Bhatt et al. 2015, 2019, 2021).

Punjab and Haryana, two small Indian states referred as "Food Bowl" for the country, produce around 50% of rice in the country (Dhillon et al. 2010). Due to excessive pumping of underground water from an area of 440,000 km^2 mainly to feed rice-based cropping systems, the rate of falls of underground water reached up to 0.3 m year^{-1} (Soni 2012). Conventionally, the water being pumped out from the below ground aquifers resulted in decline of overall water levels in the region from 1970s (Hira et al. 2004). The rate of water fall in central Punjab, India reported to hiked up to 100 cm year^{-1} from 20 cm year^{-1} from 1973–2001 to 2000–2006, mainly due to extended area for rice cultivation and the conventional faulty crop establishment and irrigation methods (Humphreys et al. 2010). Among the different sectors competing for water, agricultural sector is the chief competitor due to conventional faulty crop establishments and irrigation practices, but due to competition received from the other sectors, viz., industrial, etc., its share needs to be reduced to the tune of 10–15% in the upcoming decades. (Singh et al. 2010). Significant share of the good quality water used in the crop production sector needs to be reduced, but in a sustainable way (Rost et al. 2008; Döll et al. 2012). The unsustainable use of the underground water for establishing and irrigating rice-based cropping sequences results in water scarcity and hence, there is an urgent need to invent, test, and recommend the RCTs to the farmers of the SA region based on their soil and climatic conditions (Humphreys et al. 2010; Jat et al. 2012; Bhatt et al. 2019). For extracting, the water from the deeper depths, more and more energy is required which is already scarce due to its higher requirements in the industrial and other sector (Hira 2009). Conventionally, in sandy soils of the region, rice is established through the puddling operations (which itself required around five to six irrigations) for sealing the soil pores and reducing the drainage losses, resulting in the subsurface compaction (Sur et al. 1981; Kukal and Aggarwal 2003a) adversely affecting the growth of next upland crop like wheat (Kukal and Aggarwal 2003b) due to hindered root growth (Aggarwal et al. 1995; Kukal and Aggarwal 2003b). Hence, rice-based cropping systems are highly intensive in terms of different inputs, viz., water, labor, capital, and energy which further led to many sustainability issues (Bhatt et al. 2015, 2019).

Labor shortage during the rice transplanting is another important challenge as the system is labor-intensive. Current labor scarcity in Punjab, India might be due to implementation of several government schemes that promise at least 100 wages at their native places (Anonymous 2011). Further, current pandemic situations of Corona virus occurred during this year also adversely affect the labor availability due to hindrance in the transport modes including rail or bus services. For getting labor in time for timely transplantation of paddy, farmers provide incentives of several types to the migrant laborers. For solving the issue for labor shortage, scientists have invented mechanical transplanters that are adopted by the farmers for establishing rice in Haryana (Sharma et al. 2005; Malik and Yadav 2008). For encouraging least disturbance in the field, several workers studied ZT-MTR that involves no tillage and hence helpful in cutting down the footprints of water or energy compared to conventional puddled transplanted rice (PTR) systems. At sandy loam soils, PTR is applied with 12.5 cm lower irrigation water than transplanted rice in untilled soil (Singh et al. 2001) and that might be due to the continuity of the soil pores. Even then MTR is not popularized to the maximum extent which might be due to complex operation of growing the mat type nurseries, etc. (Bhatt 2015). Further, very little information is available on the soil water balance components in the tilled and untilled conditions. The studies in the region have shown significant water savings while jumping from continuous anaerobic conditions to alternate conditions of wet and dry conditions of 2 days (Sandhu et al. 1980) or tensiometer basis (Bhatt and Arora 2021; Bhatt 2020; Kukal et al. 2005). As compared to conventional PTR system which involved huge water volumes, direct seeded rice in the unpuddled fields keeps gaining momentum in the last decades (Bhatt and Kukal 2017). But as discussed earlier, like other RCTs, DSR is also not an exception and is reported to be successful only in the medium- to heavy-textured soils. However, on the light-textured soils, DSR proves to be a great failure due to higher weed biomass and severe iron deficiency. Moreover, due to lack of puddling operations, soil pores also do not close, which further resulted in the excess of the drainage losses. Therefore, DSR is advocated on the medium- to heavy-textured soils at the field capacity (PAU 2021) for harvesting potential land and water productivities.

Alternate wetting and drying are also advocated as an effective RCT, and based on the soil matric potential readings in a clay loam soil, significant amount of water was saved (Yadav et al. 2011a, b). Comparing the irrigation, input and ET water productivity in between different establishment methods of rice, viz., DSR and PTR, Yadav et al. (2011b) reported with higher water productivities, however, significant differences reported only under irrigation water productivity. Further, more research should be planned particularly in coarse- and medium-textured soils. A number of studies highlighted the water saving in DSR and thus higher productivities in terms of land and water but all includes the sole rice crop and almost nil studies deal with next intervening and wheat crop. It might be possible that water saving in rice may dry the soil profile and demand higher water inputs while growing wheat crop. Therefore, for critically understanding the impact of any RCT on the land or water productivity, RWCS as a whole with both crops and in between intervening periods must be studied as sole crop will not clear the whole picture.

Major sustainability issue in RWCS for management of huge bulky crop residue is the most challenging as farmers used to burn the residues onto their fields which not only adversely affects the soil health indicators but also magnifies the effects of the global warming (Jhanvi and Bhatt 2020). Among rice and wheat residues, management of the rice residues is the most challenging due to its higher silica contents as wheat residues mostly used as fodder. Farmers used to burn rice residues due to comparatively shorter intervening period between rice harvesting and wheat sowing. However, disposal of paddy straw residues by burning results in loss of soil organic matter and nutrients, C sequestration, air pollution, production of greenhouse gases, and reduction in soil microbial activity (Rasmussen et al. 1980; Kumar and Goh 2000). According to Sarkar et al. (1999), estimated production of rice and wheat straw throughout the country is around 113.6 Mt., which loaded with 1.90 Mt. of nutrients. Around 12 Mt. of straw residues of rice burnt annually only in Punjab, India causing loss of 0.7 Mt. of N along with emission of 70% CO_2, 7% CO, 0.66% CH_4, and 2.09% of N_2O (Yadvinder-Singh and Timsina 2005). To address the burning issue of rice straw, scientists in the region tried to test some alternative options for the management of the rice residues in particular. In that context, Sidhu and Beri (1989) and Beri et al. (1995) demonstrated lowered wheat yields when previous rice residues fully incorporated, which might be due to N immobilization. In this context, other viable options include wheat sowing with Happy Seeder in standing rice stubbles. Further, nowadays, straw management system is also fitted with rice harvesting combine, which spreads the rice resides uniformly in the field after churning it small pieces, where upcoming wheat can be sown easily. This practice not only handled adverse effects of the global warming sustainable but through better C-sequestration (improves the soil health) and water productivity (skipping the pre-sowing irrigation) without adversely affecting the grain yields (Fig. 1.1).

Further, several trials are in progress that are testing several microorganisms which decompose the rice residues within a short period of time for timely sowing of wheat. Conventionally, farmers used to intensive till their field with an objective of having good seed bed, weed control, and better application of irrigation water. Current research reveals that conventional practice of tillage used for establishing the wheat seedbeds resulted in bursting of bigger aggregates into smaller ones and hence exposed the earlier hidden organic matter to the microorganisms which oxidizes it to CO_2—a potential greenhouse gas into the atmosphere (Ashagrie et al. 2007; Bhatt 2015).

Sowing the wheat seed in the standing rice stubbles could helps a lot in improving the declining both lands as well water productivity (Sidhu et al. 2007, 2008) due to provided mulch benefits (Balwinder Singh et al. 2011, 2015) and due to then hindrance of burning issues which further helps in C-sequestration and thus

Fig. 1.1 View of paddy straw mulcher (**a**), Happy seeded wheat (**b**), emerging wheat seeds (**c**) without pre-sowing irrigation at Regional Research Station, Kapurthala during 2020 (Source Bhatt et al. 2021)

mitigating the adverse effects of the global warming (Bhatt 2020). Zero tillage with residues as already reported helps in partitioning higher fraction of the soil moisture from the E to T component, which further improved the nutrient inflows in the plants through the roots to produce more grains to feed escalating population of the region. Further, provided crop residues help in improving different soil properties and hence soil health by one or the other way (Singh et al. 2005; Palese et al. 2014; Zheng et al. 2015; Paccard et al. 2015), while conventional tillage negatively influenced the soil properties (Roper et al. 2013, b; Das et al. 2014; Kuotsu et al. 2014b). Along with positive effects, zero tillage in the literature also reported adverse effects (Chopra and Chopra 2010; Singh et al. 2015), which might be due to the differences in the soil textural class, rainfall patterns, and management practices (Singh et al. 2015). Moreover, effect of different RCTs must be studied with respect to the land and water productivity of the complete RWCS system, as most studies include only single crop and also missed the intervening periods. Therefore, for improving the land productivity of the RWCS as a whole and for mitigating the adverse effects of the global warming, scientists in the region, invented, tested, and recommended several RCTs to the farmers of SA which includes include zero tillage, mulching, need-based site-specific fertilization and crop residue management for reducing C-footprints, short-duration cultivars, laser land leveling, soil matric potential (SMP) based scheduling, bed planting, timely transplanting, crop diversification, direct seeded rice, drip and sprinkler irrigations for reducing water footprints, mechanical transplanting, and Happy Seeder for reducing the energy footprints in the region for achieving overall food and environmental security in a sustainable and climate smart way which further reduced the degradation of natural resources and improved use efficiency of different inputs in agriculture. Most of these so-called RCTs focused on basic conservation agriculture principles, viz., conservation tillage, crop residues use as mulch (Hobbs et al. 2008; Jeffery et al. 2012), and irrigation on conservation basis (Kukal et al. 2005; Bhatt 2020; Singh and Sidhu 2014). Hence, an integrated approach of these RCTs must be discovered, experienced, and then propagated between the end users based on their conditions of soil textural class, water availability, and agro-climatic conditions.

1.2 Strategies to Inputs Use Efficiency

1.2.1 Zero Tillage

Among the different resource-conserving technologies (RCTs) propagated in the region for sustainably improving the yields, zero-tillage (ZT) is the one showing wide adoption in the IGP of SA region (Gupta and Sayre 2007; Gupta and Seth 2007). Different soil properties improved with the adoption of ZT but only after retaining full crop residues (Kumar and Goh 2000; Paccard et al. 2015), which resulted in improved soil physicochemical properties (Palese et al. 2014; Zheng et al. 2015), whereas intensive tillage splits the larger aggregates into the smaller ones and then exposed the hidden organic matter to microorganisms which oxidize this to CO_2, a potential greenhouse gas (Jat et al. 2009; Roper et al. 2013, b; Das et al. 2014; Kuotsu et al. 2014b; Bhatt 2020). Further, zero tillage in rice and wheat crop also was supposed to enhance different properties, which improved the land productivities and overall livelihoods of the farmers (Jat et al. 2014; John and Singh 2007; Strudley et al. 2008). In their four-year experiments, Luancheng, Hebei province, Zhou et al. (2011) revealed aggregates with higher size and stability under ZT plots compared to other tillage systems. Further, surface placed residues in the ZT plots improve the infiltration rate of water (Lang and Mallett 1984) and reduce runoff (Rockwood and Lal 1974), while Lindstrom et al. (1984) revealed higher soil compaction, which further resulted in lower hydraulic properties and infiltration rate, which further resulted in the poor moisture and nutrients inflows in these plots. Conservation tillage was also gaining momentum day by day due to its effective role in improving the soil health indicators as well as livelihoods of the farmers (Madejon et al. 2009; Rockström et al. 2009).

1.2.2 Mulching

Popular RWCS resulted in the production of huge crop biomass in the tune of around over 500 million tons (Mt) in India alone, sustainable management of which is a great challenge in front of the agricultural scientists and environmentalists (MNRE 2009). After the mechanical cereal harvesting in Punjab, anchored straw of

0.3–0.6 m high with loose straw in windrows seems to be problematic. Wheat straw is usually used in the animal husbandry as a fodder; however, rice straw management (>7 t ha^{-1}) is a challenge due to its higher silica content being not preferred as fodder. In between the solutions proposed by the scientists, use of paddy straw as a Mulch is the best option as it conserves the soil moisture, regulates the soil temperature, reduces vapor pressure and vapor lifting capacity of the air (Bhatt and Khera 2006), improving the inherent soil organic matter and thereby different physicochemical properties that pertain to the soil (Bhatt et al. 2019; Samra et al. 2003; Yadvinder-Singh and Singh 2005). However, in other condition, if not managed at the field, then results in burning of straw mostly of rice followed by wheat and sugarcane trash to the tune of around 40, 22, and 20%, respectively, (Jain et al. 2014) results in the production of 8.57 Mt. of CO, 141.15 Mt. of CO_2, 0.037 Mt. of SO_2, 0.23 Mt. of NO_2, 0.12 Mt. of NH_3, and 1.21 Mt. of particulate matter during 2008–2009, which is not desired. Rice straw loaded with nutrients, viz., N (40%), P (30–35%), K (80–85%), and S (40–50%) (Dobermann and Fairhurst 2002) which if burnt is of no use, rather adds to the global warming. Around 0.54 MT of NPK is recycled annually considering rice and wheat residues to the tune of 90 and 30%, respectively. Hence, instead of burning them up, they must be used as mulch onto their fields or may be recycled in other forms, viz., paddy compost which further adds to the fertility of the soils.

1.2.3 Need-Based Site Specific Fertilization

For the effective and sustainable use of the fertilizers, scientists invented some gadgets which help in the plant-need-based applications as plants, but not the soil, is to be fed. In this series, some approaches, viz., soil-test-based fertilization is the basic while leaf color chart, chlorophyll meter or SPAD, green seeker, and leaf analysis are advanced techniques, which guide the farmers to reduce overall costs of cultivation and sustainably manage the ecosystem in another way. Some gadgets provide details of biophysical and biochemical information of crop for deciding their need to have potential yields (Darvishzadeh et al. 2019). Several workers already used these gadgets in many crops, viz., sugarcane (Singh et al. 2006; Portz et al. 2011), rice (Bijay-Singh et al. 2015), wheat (Heege et al. 2008), and cotton (Raper et al. 2013, b) corn (Tremblay et al. 2012), and barley (Soderstron et al. 2010). Following is the discussion of these techniques/gadgets one by one on how these works for the better management of the fertilizer's usage.

1.2.3.1 Soil Test Based Fertilization

Among the different plant-need-based approaches, soil-test-based fertilization is the most important one as it delineates the inherent fertility of the soil to supply different plant nutrients to the plants for having the potential yields in a sustainable manner (Bhatt and Sharma 2014; Arora et al. 2020). This is the only technique which is discussed quite often in every farmer welfare or agricultural camps, *especially scientific technique of collecting the soils samples for different purposes*. A number of soil-testing labs are functional at the district levels which might be at the Krishi Vigyan Kendras, Markfed, or other governmental agencies after charging nominal charges from the farmers. Even policies are in the way to provide subsidized fertilizers to only those who test their soils. The aim is to reduce the leakage in the underground water or in the atmosphere as both are proved to be harmful, which might cause eutrophication or global warming (Bhatt 2020). At last, farmers have to care for certain factors while collecting the soil samples as they do not need to collect samples from the shade of any tree, near from any farm yard manure heap, near the water channels, or any unusual spot.

1.2.3.2 Leaf Color Chart/Green Seeker

Second approach which is also quite important based on the asking from the plants itself that is by comparing colors of the LCC and the leaves of the plants (Fig. 1.2a, b). This approach really works as it proved to be a managerial tool for the N management in the field crop as lower doses result in lower yields while higher doses result in emission of greenhouse gases. LCC gadget comprises the strips comprised of high-quality plastic delineating different greenness shades from lighter to darker side and works as per chlorophyll meter in the field (Varinderpal-Singh et al. 2010). Its first testing launched in Japan for the first time from where it is modified into six-panel LCC (IRRI 2009) which further advanced in the year 2007 to

Fig. 1.2 Different gadgets advocated in the region for the site-specific nutrient management, viz., Leaf color chart (**a**), seeker (**b**), and front and chlorophyll or SPAD meter (**c**)

four-panel strip (Fairhurst et al. 2007). Further, with the advancement in LCC, it changed to eight-panel (3, 4, 5, 5.5, 6, 6.5, 7 and 8) (ZAU-LCC) in 2013 (Yang et al. 2008) and then to eight-panel (1–8) (UCD-LCC) was developed (Boyd 2001) for estimating percent leaf nitrogen. LCC already recommended in the rice, wheat, and some other crops in Punjab, India, where farmers used them for the efficient utilization of the N fertilizers (PAU 2021). Further, green seeker also evaluates the leaf greenness in a digital mode and helps us to judge performance of different RCTs in improving the land as well as water productivity (Fig. 1.2).

1.2.3.3 Chlorophyll Meter

For sustainable nitrogen management in the region in a climate smart way, SPAD is recommended and used successfully in the experimental trials (Fig. 1.2c). Quite often, N-demand of plant is estimated based on soil and leaf N inherent status, which required lab analysis which is costly and involves huge time. Hence, a gadget is required which provides us spontaneous estimate regarding leaf greenness under different treatments and proved to be quick managerial tool for application of nitrogen in the crop field (Akhter et al. 2016). Mostly used popular SPAD meter which is a quick, non-destructive and portable is Minolta SPAD-502 developed by Minolta Limited, Osaka, Japan (Minolta 1989) which quickly provides leaf greenness as chlorophyll content (Feibo et al. 1997; Boggs et al. 2003). Fieldscout CM 1000 is an advanced SPAD being developed by Spectrum Technologies, Inc. (2009) and it is based on the principle of running average of multiple readings, where data get recorded in the data logger (Varinderpal-Singh et al. 2012).

1.2.3.4 Omission Plot Technique

This is also an important intervention for sustainable fertilizer use where yield is already targeted and then based on the soil and climatic conditions, fertilizers are applied accordingly. Under this approach, all the nutrients are applied except the nutrient under consideration to have a look on its role in the overall yield. Running on the same track, Khurana et al. (2008) also conducted such trials at 56 locations of India and concludes that higher land productivity of wheat plots with accumulation of different nutrients, viz., N, P, and K jumps to 12–20% in plants followed by 13% higher gross returns than with farmers' practice. Hence, the OPT helps to estimate the critical role played by each nutrient in achieving the sustained yields in a sustainable manner while mitigating the adverse effects of the global warming.

1.2.3.5 Using Nutrient Expert

Nutrient expert (NE) is the important computer-based decision support program that dictates around the factual position of the field, which further helps in the sustainable usage of the fertilizers with least adverse effects on the ecology (Pampolino et al. 2008; Varinderpal-Singh et al. 2012). Generally, NE established depends on the last 3–5 years of research carried out in the texturally divergent soils, the previously applied fertilizers, actual and reasonable yield, different soil fertility indicators, content of residue produced, and information pertaining to need based and site and soil texture specific fertilizer recommendation (Dass et al. 2014). Further, for improving the use efficiencies of applied N inputs and to meet the plant N requirements sustainably in a climate smart mode, model is designed (Sapkota et al. 2014). The idea is to improve the fertilizer use efficiency by applying nutrients in the form of fertilizers as and when required by the plants, which further mottled with soils having different texture, viz., different proportion of sand, silt and clay, and variable rainfall patterns. With this approach, yields improved to feed the burgeoning population in a climate smart way (Bhatt et al. 2019).

1.2.4 Crop Residue Management

1.2.4.1 Biochar/Paralichar

Even now, crop residue management is challenging but the concept of biochar/paralichar solved this challenge to the great extent, which is entirely based on the pyrolysis, gasification, and hydrothermal carbonization, which constitutes up to ~70% of C that might otherwise escape into the atmosphere and have serious complications including global warming. Biochar application in the agricultural fields helps in improving the inherent soil organic carbon and thus other physico-chemical and biological properties (Sohi et al. 2010; Day et al. 2005; Srinivasarao et al. 2012, 2013). Punjab Agricultural University, Ludhiana, Punjab pioneer agricultural university considering this aspect recommended farmers friendly ‘Paralichar’ having 30–36% C with an idea to avoid straw burning and to enhance the C sequestration for finally reducing the C footprints. *Parali Char* is prepared in a dome-type kiln, composed of bricks and clay (height = 14 ft., diameter = 10 ft) and can accommodate 12 t of rice straw (Fig. 1.3). This dome-shaped pyramid has two windows, one at the top and another at bottom of the kiln for loading of rice straw. In addition, six vents of 2-inch diameter in the upper portion and eight vents are provided at three heights on the remaining portion of the structure. The whole process of making *paralichar* usually takes ~10–12 h. On an average, *paralichar*

Fig. 1.3 Dome of paralichar in action. Source: Purakayastha et al. (2015)

contains 30–36% C, 0.5–0.6% N, 0.16–0.22% P, and 1.6–2.2% K. Its field application in rice and wheat at 5 t ha^{-1} saves 40 kg N ha^{-1} and increases crop productivity and improves soil health. Being a fine-grained, soft, C-rich source with highly porous structure and high-surface area, biochars are considered important in view point of C sequestration and for reducing C footprints of the RWCS in the region. Another application of the biochar includes the reclamation of acid soils, which further enhanced the production potential of such soils. Biochars also helps in mitigating the adverse effects of the global warming as it stores the recalcitrant C pool in soil and hence mitigates ~12–50% of anthropogenic C emissions (Cayuela et al. 2014). Being prepared under limited O_2 supply, biochar restricted the emissions of greenhouse gases and also improved the SOC. Many a times, thermal decomposition is also used for preparing the C-rich biochar by heating the residues anaerobically (Sohi et al. 2009). Therefore, biochar/parailichar serves in two ways: first by reducing C emissions in the atmosphere and thereby mitigating the climate change consequences while also enhancing the inherent SOC and the soil properties and livelihoods of the farmers in the region (Srinivasarao et al. 2013).

1.2.4.2 Paddy Compost

Considering the need for the small farmers, preparation of the compost from the paddy straw is also a viable and sustainable option, where farmers could use residues and improve their livelihoods. Punjab Agricultural University, Ludhiana, Punjab, a pioneer agricultural university of the country, considered this aspect and recommended farmers to go for paddy compost. For preparing it, a farmer needs to first collect rice straw from his field and shift the material near a tube well. Further, straw needs to be tied up into about 10–15 kg bundles. Afterwards, “soaking solution” is prepared by thoroughly mixing 1 kg cow dung for every 1000 liter of water in a big tank, wherein the bundles were dipped for 4–5 min. Afterwards, the excess water is drained off by placing wet bundles onto a sloppy land, which could further be reused. Make 15 cm raised beds 5 m long and 1.5 m wide on the ground, which helps in draining water from the heaps. When water drainage stops, place 2–6 cm diameter tree branches/sticks to provide aerated conditions to the wetted straw, loaded with around 70% moisture. Afterwards, these bundles are stacked into 500 kg heaps sprayed with powdered low-grade rock phosphate at the rate of 6% on dry weight basis of the rice straw approximately. 500 kg of rice straw normally assumed a height of 150 cm and rice straw can be composted in multiple lines with a spacing of 1.0 m for uniformly irrigating the straw heaps. For reducing the evaporation losses and for maintaining 70% moisture in the heaps, the moist straw must be covered by 20–30 cm thick layer of dry straw. Any major error in this step will delay composting. Moisten straw heaps frequently uses watering lance with a sharp point, so that water could enter deep in the bundles. After a period of 3 months of moistening, the paddy straw gets decomposed to the extent that straw are weak and get broken on twisting. At this stage, the paddy compost is ready to be used in the field as at this time C:N ratio becomes to 15:1.

1.2.4.3 Other Options

Some other paddy compost management options also are recommended by the Punjab Agricultural University, (PAU) Ludhiana for farmers which include the following:

1. Straw baler could be used for preparing the paddy straw bales after combine rice harvesting. These bales are prepared after reducing the size of straw by chopping the standing stubbles with stubble shaver and could be used into the different purposes mentioned below.
2. Electricity production: In Punjab, India, up to seven biomass power plants have been established for electricity production which consumes paddy straw bales as basic input. By burning paddy straw under controlled conditions, the produced heat used to run the steam turbine. Farmers in these regions, instead of burning, sold these bales to these power plants.
3. Paddy straw based biogas plant: Potential biogas could also be generated in the specially designed biogas plant from the paddy straw. Around 1600 kg of chopped paddy straw could be used along with 400–500 kg of cattle dung, which provides around 6–7 m^3 biogas on a daily basis.
4. Paddy straw geyser: PAU, Ludhiana also developed a geyser which used the paddy straw bales for heating the water. Generally, under the normal conditions, around 102 l of water could be warmed up to 45–50° C for 4 h which remained at this temperature for different uses up to 24 h or even more.
5. Outdoor sofas: PAU, Ludhiana also prepared outdoor sofas and central table for the daily use and in this attempt, these sofas were placed outside the communication center of the university for the visitors (Fig. 1.4). Stubbles of paddy straw from half acre are used to prepare four sofas and central table.

1.3 Water Footprints for Food and Environmental Security

1.3.1 Short Duration Rice Cultivars

Traditionally, farmers used to grow the long-duration cultivars, viz., Pusa-44 due to their higher yield potential but on other side required significantly higher irrigation water for meeting the evaporative demand of atmosphere and plant needs as compared to the short- or medium-duration cultivars (Bhatt et al. 2019). Moreover, due to use of higher amounts of fertilizers and water, their leaves become succulent which are attacked by the insect pests, which ultimately also reflects in the yields. However, on the other side, if farmers opted for the short-duration rice cultivars, then their presence in the field and required irrigations will also be reduced with lesser number of attacks, viz., PR-126 and PR-127 (recommended for cultivation in Punjab) which take only around 123 and 137 days and could save the irrigation water to the tune of 15–20% (Singh et al. 2015; PAU 2021). Hence, growing of short-duration rice cultivars is an important RCT, which sustainably minimizes the water footprints of the rice-based cropping sequences in the region.

Fig. 1.4 Prepared furniture from paddy stubble as an option to straw burning for reducing C footprints by PAU, Ludhiana (Source: https://www.hindustantimes.com)

1.3.2 Date of Rice Transplanting

This is a scientifically proven RCT which reduces the water footprints without cutting down the drainage losses (Humphreys et al. 2010). Inherently, farmers as per their indigenous knowledge sow nurseries in May and transplant it in the same month. Now, as temperature and evaporative demands of atmosphere are quite higher, most of the applied water are lost to satisfy these components, and very lesser proportion remained for meeting the plants requirements. In that attempt, farmers need to frequently irrigate their fields which overall enhances the water footprints of rice-based cropping sequence. However, if the farmer sows nursery in May and transplants it after June 10, then things totally change, as upcoming months coincide with the monsoon rains, which moist the dry air and reduces its evaporative demands and hence, water lifted by air is reduced and as a result the frequency of applying irrigation water is reduced which further cut down the overall water footprints. (Bhatt and Kukal 2017; Mahajan et al. 2011; Sharma et al. 2011). Running on the same track, Jalota et al. (2009) recorded 17% higher crop water productivity in the paddy crop, where nurseries were transplanted on June 25, in comparison to the crop transplanted the month earlier. Singh et al. (2017) also reported higher CWP for timely transplanted rice on June 20, than for the earlier planting, i.e., June 5.

1.3.3 Direct Seeding of Rice

After recognizing the adverse effects of the puddling onto the soil structure, soil physicochemical properties, next upland crop and finally on the water footprints, scientists invented, tested, and recommended a new techniques of rice establishment, which escapes from the puddling operations and all the adverse effects caused by it known as direct seeded rice (DSR). From the last decade, it is being recommended in the entire region, without considering the benefits of puddling, which are not here such as, firstly severe iron deficiency and secondly significantly higher weed biomass (Bhatt and Singh 2021; Bhatt and Kukal 2015a, 2021; Mahajan et al. 2011). Both of these factors cut down the DSR adoption in the region. Scientists relooked into it and they observe that DSR is not universally applicable rather depending on the soil textural class and hence, must be advocated for the farmers having medium to heavy textured soils. Otherwise, in sandy soils, DSR proves to be a great failure due to the reasons above. Hence, farmer must adopt this RCT only at medium- to heavy-textured soils at the field capacity (PAU 2021).

1.3.4 Laser Land Leveling

Laser land leveling (LLL) is the most adopted RCT in the region by the farmers for reducing their water footprints in the region, which further helps in improving the efficiency of irrigation water and other input use efficiency for food and environmental security. This RCT levels all the unleveled points of the field and ensures even distribution of irrigation water and covers a more area within a shorter period of time. Further, up to 30% of irrigation water might be saved by the LLL without making any yields penalty (Bhatt and Sharma 2009; Jat et al. 2009). As per Jat et al. (2006), LLL recorded with potential to reduce irrigation water and electricity sustainably by ~25%, which further promoted the land productivity of the rice-based cropping system to about ~4% than the conventional leveling. IWP for laser-leveled rice fields is increased by ~39%, compared with the conventionally flooded field. Due to the perfect leveling, applied irrigation water distributed quickly in a short span of time which further reduces the weed infestation. In this regard, cut off the herbicide cost to around ~13% in rice fields than the farmers' practice of weed management. The LLL technology has an enormous potential for optimizing WUE in rice, without any yield loss (Kaur et al. 2012). Hence, this technology is the really effective in reducing the water footprints by one or the other way. Only limitation associated with this RCT is the higher costs of the leveler, which could be easily solved by custom hiring.

1.3.5 Permanent Beds

The bed planting, also considered as an important RCT for reducing the water footprints up to the tune of 20–30%, was first tried for wheat Mexico and later for

Table 1.1 Performance of bed planted wheat over other establishment techniques (Data source: Brar et al. 2011)

Establishment method in wheat	Water productivity (g m^{-3})		
	Direct seeded basmati rice	Transplanted basmati	Mean
Conventional sown wheat	384.21	366.5	375.4
Bed planted wheat	388.0	366.4	377.2
Zero till wheat	374.6	359.4	367.0
Mean	382.3	364.1	

Table 1.2 Root mass density (mg cm^{-3}) of rice grown on fresh and permanent beds (Data source: Kukal et al. 2008)

Soil depth (cm)	Fresh beds	Permanent beds
0–5	2.078^{a}	1.209^{b}
5–10	1.524^{a}	0.957^{b}
10–15	0.359^{a}	0.320^{b}
15–20	0.149^{a}	0.141^{a}
20–25	0.041^{a}	0.063^{a}
25–30	0.036^{a}	0.043^{a}
0–30	0.698	0.456

rice (Singh et al. 2005). In the heavy less permeable soils, aeration could be solved with the bed planting. Beds also claimed to increase the thickness of basal internodes, saved total water quantum applied, and finally improved the water productivity and cut down the total water footprints. Furthermore, N recovery and hence final yields also claimed to be higher in beds (Brar et al. 2011) (Table 1.1).

But this RCT also suffers from the temporal (time) (Table 1.2) effects as fresh beds are quite effective and as they age, reshaping operations are required with tractor and due to the effect of extra pressure exerted by the tractor tyres, the side slope of these beds get pressed, which results in their compaction and poor root mass density.

Further, it results in the yield penalty due to deteriorated soil properties as bulk density reported to be higher in the aged bed. Hence, these beds need to be re-prepared after every 2–3 years depending on the soil textural class (Kukal et al. 2008) (Table 1.2; Fig. 1.5). To handle this problem, tractor used must be of narrow tyres. Rice land productivity diminished to 19% in 2004, 45% in 2005, and 59% in 2006 from 4.64 t ha^{-1} in 2003. Root mass density was reported to be 59% higher on the permanent beds compared to the fresh beds. Hence, efficiency of the fresh beds seems to be decreased as the beds get older and older due to increased bulk density (Kukal et al. 2008).

1.3.6 Soil Matric Potential Based Irrigation

Before this RCT, there is no gadget for the farmer which dictates them when to irrigate the field depending the conditions. Irrigation scheduling based on the soil matric potential really helps to cut down the water footprints to a level of significance

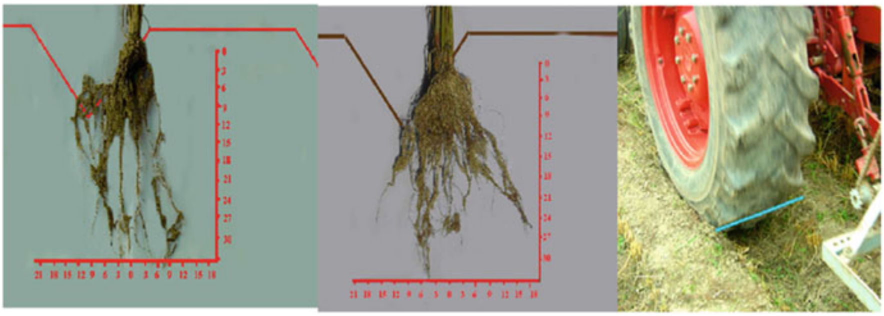
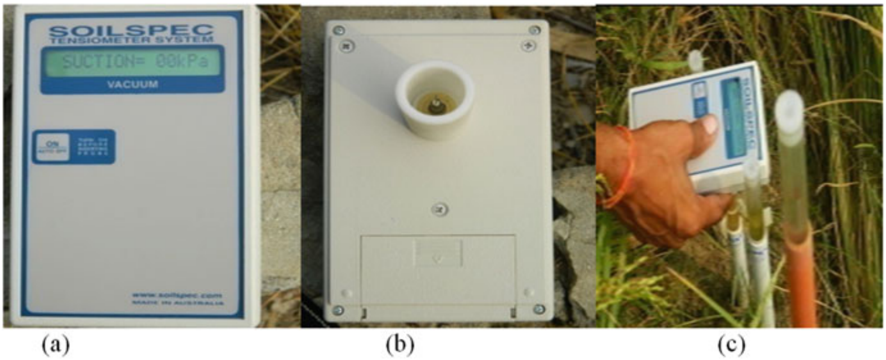


Fig. 1.5 Effect of beds on the root growth and view of compaction of side slopes of the furrows during reshaping operations as the beds aged (Source: Kukal et al. 2008)



(a) (b) (c)

Fig. 1.6 Soil spec front view (**a**), rear view (**b**), and in action measuring soil water tension (**c**)

(Bhatt 2020). Moreover, with wrong conventional indigenous system, the water levels below ground are declining at a faster rate which further led to water stressed conditions (Hira 2009; Bhatt 2015, 2019). As per one estimate, annually extra withdrawal of underground water principally for the rice irrigation is >13 Lakh ha-m, which further declines the underground levels of water. Based on matric potential concept, tensiometer guided the farmers particularly of stressed regions regarding when to irrigate the paddy fields (Fig. 1.6). While evaluating the success of the tensiometer, Bhatt and Sharma (2010) revealed water saving from the tune of 11.1–30.7% from 2006 to 2010 which further helps to cut down the water footprints of rice-based cropping sequence by applying water as and when required in right quantity. Tensiometer also takes care of the soil texture as dictates more number of irrigations for sandy soils as compared to the heavy-textured soils. Tensiometer cut off the drainage losses of water, hence reducing its water recharging potentials (Humphreys et al. 2010). Hence, this is reported to be a very good technique where water-logged conditions is problematic, viz., Southwestern Punjab. Tensiometer, being a water footprint cutting technology, particularly in rice-based cropping sequence is promoted in the region by many extension agencies but even then it is not adopted to the desired levels, and a number of factors, both direct and indirect, are recognized (Bhatt 2020).

1.3.7 Crop Diversification

Rice-based cropping sequence is the major consumer of the irrigation water inputs due to unsustainable and wrongly adopted techniques. RCTs are advocated in the regions to the farmers for reducing the water footprints depending on the certain site- and situation-specific conditions. A number of technologies being termed as RCTs are propagated in the region for reducing the water footprints but all are site- and situation-specific. The only effective way is to replace the more water-demanding rice crop with other lesser water demanding crop, viz., maize, etc., for sustainably improving the declining soil health and livelihoods of the farmers. As per one estimate, crop diversification with maize improves the soil health as it does not include the operation of puddling, thereby preventing the soil structure deterioration and cutting down the water footprints and water productivity in a sustainable way (Jain and Kumar 2007). As per Johl committee report presented in the year 2002, at least 1.0 M ha area must be diverted from the rice to other less water requiring crops (Table 1.3). Hence, crop diversification of rice with basmati rice, maize, pulses, and wheat with raya and chickpea provides a viable and win–win technology for the farmers of the region to cut down the water footprints in a sustainable way by reducing the evapotranspiration water requirements.

1.4 Energy Footprints for Food and Environmental Security

1.4.1 Mechanical Transplanting of Rice

Rice-based cropping sequence often claimed to be highly capital, labor, water, and finally energy-intensive due to extensive cultivation operations involved in the puddling operations, which further adversely affected many soil physicochemical properties and finally yields (Bhatt 2020). Shortage of labor now emerged as chief challenge due to limited window period and imposed rule for paddy transplanting

Table 1.3 Crop diversification impact in improving water productivity. Source: Jalota and Arora (2002)

Annual loss of water (mm) including intervening periods				
	Medium textured soils		Coarse-textured soils	
Cropping system	ET	Deep drainage	ET	Deep drainage
Rice-wheat	1130	810	960	770
Maize-wheat	1080	410	890	650
Cotton-wheat	1340	280	1210	500
Sugarcane	1360	210	1340	550

after June 10 which urgently needs to be addressed for sustainable rice-based cropping systems (Bhatt and Kukal 2015c; Humphreys et al. 2010). Due to implementation of the different scheme of Govt. of India, viz., MANREGA (GOI 2011), the issue attained an alarming situation. Thereby, to face this challenge sustainably, Mechanical Transplanting of Rice (MTR) is one viable option (Garg et al. 1997; Prasad and Power 1997; Kamboj et al. 2013; Bhatt et al. 2014). Conventional transplanting of rice seedlings is more laborious and time-consuming which required around 300–350 man-h ha^{-1} and a worker dips fingers 1,40,000 times to transplant one acre of land with rice seedlings (Rao and Pardhan 1973). To reduce the energy inputs and to avoid ill effects of puddling, MTR recommended the dry cultivated (Singh et al. 2005; Duraisamy et al. 2011) or uncultivated soils (Malik and Yadav 2008; Sharma et al. 2003, 2005). However, MTR also, like other RCTs, is suffering from many disadvantages (Bhatt et al. 2015) out of which growing of mat-type nursery is the most limiting factor followed by the costly machinery and technical drivers. These could be addressed by the intervention of governmental and private sector for making it a largely adopted RCT for reducing the energy inputs in the RWCS of the region.

1.4.2 Happy Seeder

Happy Seeder is an important intervention in the region for RWCS for reducing the energy and water inputs by directly sowing the wheat seeds in the standing rice stubbles after combine rice harvesting without any pre-sowing irrigation. Earlier zero till drill promoted in the region (Harrington and Hobbs 2009), which escapes the intensive tillage operations and allowed timely wheat sowing, but here loose rice straw has to be managed which normally farmers do by open burning which is not desired at all in the region. Further, intervention of “Happy Seeder” allowed the direct sowing of wheat seed (Sidhu et al. 2007, 2008) side by side cutting and removing the loose straw in the way of the sowing types, thereby spreading the straw cover on the bare soil which then provides the benefits of the mulch (Bhatt and Khera 2006; Sidhu et al. 2008). Hence, Happy Seeder wheat sowing based on zero tillage concept with full straw loads improved the yields (Paccard et al. 2015), water use efficiency (Guan et al. 2015), carbon sequestration (Zhangliu et al. 2015), improved soil structure (Singh et al. 2005), and livelihoods of the farmers (Tripathi et al. 2013). Further by reducing the soil evaporation, share of evaporation partitioned towards the transpiration which further reported to enhance the nutrient inflows and finally improves the yields (Sidhu et al. 2008; Deng and Byrne 2006). Thereby, farmers of the region need to be educated regarding this which further results in the maximum adoption of this RCT in the RWCS of the region.

1.5 Impact of RCTs on the Soil Properties

Though a number of technologies are known to conserve the resources, viz., short duration varieties, timely planting of rice seedlings, direct seeding of rice, zero tillage, laser leveling, bed planting, soil matric potential-based irrigation with tensiometer, etc., are being recommended in the region which definitely affected the soil properties by one or the other way but generally statistically at par. Bhatt and Kukal (2015e, f) reported in their two-year study that these RCTs are not universally effective, rather site- and situation-dependent and required a set period of time ranging from three to 5 years to affect the soil properties significantly. Hence, up to that period, these RCT's effect on the soil properties is at par. Many contradictory studies are also there in this direction which reported the significant effect of these RCTs on the soil properties within 2 years but proper explanation to this fact is not very well discussed over there.

1.6 Conservation Agriculture

For bringing the long-term sustainability in the RWCS of IGP, improving the livelihoods and to practice climate smart agriculture in the region, conservation agriculture (CA) is introduced (Bhatt et al. 2015; Jat et al. 2011; Bhan and Behera 2014). As far as different principles of CA are concerned, normally it belongs to three principal pillars: the first based on the crop diversification, second consists of the minimum or reduced tillage, and last, retaining residue mulch onto the surface of the soil (Bhatt et al. 2015; Farooq and Siddique 2015). Growing the same cropping sequence year after years results in the depletion of specific nutrients from a particular soil depth, which further results in reduced productivities thereafter. Hence to come out of this situation, replacement of the rice with maize reduces the water footprints and also improves the soil structure as maize cultivation escapes from the puddling adverse effects (Dobermann and Witt 2000; Balota et al. 2004). The second principle of CA promoted the minimum tillage and avoids intensive tillage operations as later tillage option produces enormous greenhouse gases, viz., CO_2 into the atmosphere (Bhatt et al. 2021; Bhatt 2015). Further, covering the soil surface with crop residues is the best intervention as it regulates the soil temperature, reduces vapor outflows from ground surface, reduces speed of the air and their vapor lifting capacity, and finally reduces the evaporation (Singh et al. 2011) and improves the use efficiency of applied irrigation water (Kukal et al. 2014), preserving the soil moisture more particularly in the intervening periods (Bhatt and Khera 2006; Bhatt and Kukal 2015a, b, c, d). Hence, the adoption of CA on one side improved the yields by improving the soil organic matter status while on the other helps to practice the climate smart agriculture, which helps to practice sustainable agriculture and improve the livelihoods of the farmers of the region (Kirkegaard and Hunt 2010; Chan et al. 2011; Epule et al. 2011).

1.7 Reducing Food Loss and Wastage for Reduced Global Food Production Targets

For sustainably achieving the food production target in the region, where on one side, food grains production needs to be enhanced and on the other side, food loss and food wastage must be addressed so that produced food can satisfy the maximum number of the inhabitants of the region (Bhatt et al. 2015; Bhatt et al. 2019). In general, agricultural farms are globally able to fulfill the grain requirements of vegetarians but are not recovered due to the complexities, inefficiencies, and incongruities in the food system that many suffer from hunger and malnutrition. Due to escalating global population, target to produce more and more food from the limited resources of land and water is a great challenge. In the capacity to produce more food grains, farmers used to add more input without caring to improve their use efficiency rather, which further have adverse consequences on the ecosystem as a whole. One of the prime factors for escalated production target is the loss/wastage of the produced grains, which certainly needs to be arrested at the source. As per one estimate, around 1.3 billion tons of food go to waste or are lost (Ayeleru et al. 2016), and almost no work is done in this regard. Hence, on one side, around 800 million people slept hungry daily while on the other side, a lot got wasted. With every wasted food grain/fruit/vegetable/milk drop, the embedded nutrition, energy, water, capital, and other resources are also wasted, which cannot be tolerated at any costs. Hence, government must prepare the good roads which linked villages with the markets and good storage centers with proper control of rats. Further, people must be aware to not waste their food more particularly in the marriages or birthday or other social functions so that the food going to waste could be diverted to the poor in a sustainable and climate smart way, reducing the food grain production targets.

1.8 Conclusions, Identified Gaps, and Upcoming Strategies

RCTs advocated in the region for sustainably feeding the globally escalating population from shrinking natural resources are site- and context-specific, and are not universally applicable. For example, direct seeding of rice grains in unpuddled soils, reported to be poor performance in the light-textured soils, aged beds reported with lesser productivity due to higher bulk density caused on reshaping the aged beds etc., MTR due to growing of complex mat type nursery, tensiometer due to complex working operations etc. Further, among all RCTs, only short-duration rice varieties and timely rice seedling transplanting seem to be real water saving technologies as it prohibit cutting off the drainage loss, hence required in the water-stressed regions. However, all the other RCTs expected to cut off the drainage losses claimed to be effected only in the water logged regions and better known as “energy saving technologies,” which must be used in uplifting the water from the deeper underground depths. Hence, generally it seems to be difficult for the farmers to pick up a single or a set of technologies for improving the use efficiency of the applied inputs, which further helps in reducing the C, water, fertilizers, and pesticides footprints.

Better selection of the available options as per ones conditions of soil, water, and climate helps in mitigating the adverse consequences of climate change by reducing GHGs emissions and improving soil health and yields. Thereby, an integrated approach or guidelines must be there for the farmers while selecting and adopting certain RCTs (pertaining to their soil textural class and agro-climatic conditions) for improving their yield potentials in the region. Moreover, the issues of food wastage/loss must be handled through the suitable policies of government or farmer produce organizations which further helps in addressing long-term sustainability of RWCS related to reducing different footprints pertaining to carbon, water, and energy. Finally, the above discussion revealed that direct seeding or mechanical transplanting in rice under zero tilled plots while minimum or zero tillage with full straw loads in wheat proves to be an important intervention which also shared the benefits of the mulching and partition maximum share of the E to T, thereby improved the attainable yields without adding more of water, fertilizers or pesticides.

1.8.1 Identified Gaps

Agricultural scientists have invented, tested, and recommended different conservation technologies which help to improve the yields and thus livelihoods along with conserving natural resources in a more sustainable manner. However, all of them are not equally effective in serving the purpose and depends on the local conditions of soil, water, and climate. This means these proposed RCTs are effective in one region and prove to be totally ineffective in other. Thus, it means that some research gaps are there which need to be sustainably filled up for these RCTs to cover larger area of RWCS in the region. Following are some identified gaps:

1. Different research programs must consider RWCS as a whole instead of working on sole wheat or rice crop as RCT adopted for establishing one crop has an effect on the next crop. Further, water saved under one RCT used for establishing one crop results in higher water demands of the next crop.
2. Studies on the intervening period generally missed in most of the studies as workers mostly engaged in evaluating the adopted RCT's performance on crop under study. Intervening period is very important and its proper investigation is very important for cultivation of different intervening crops, viz., fodder and legumes, etc., which further affected the next crop and its achievable yields.
3. Soil–water balance must be delineated in rice or wheat crop for evaluating the effect of applied technology.
4. Generally, minimum or zero tillage is promoted for sequestering more and more of carbon, but field under this technique reported micronutrient deficiencies, viz., iron, followed by hike in the bulk density of soils. Hence, proper research strategies as per ones' soil, water, and rainfall patterns must be worked out under different research programs for popularizing this important RCT.
5. Importance of mulching must be demonstrated to the farmers for its role in improving SOC, soil properties, yields, and finally their incomes. This helps to

reduce the burning of crop residues in open which further helps to alleviate the undesirable effects of climate change.

1.8.2 Upcoming Strategies

Based on the above discussions, some strategies are formulated which must be considered while making the plans on RCTs to achieve higher yields and water use efficiency, better soil health, minimize greenhouse gas emissions, and to reduce the energy, water, pesticide, and carbon footprints

1. Crop residues must be retained on the bare soil surface to regulate the soil temperature, vapor pressure gradient, outflow of the water vapors which further greater partition higher part of evaporation to the transpiration, which further reflected in higher nutrient inflows in the plants and recorded overall better yields sustainably. Hence, instead of burning crop residues must be applied onto the soil surface.
2. Different RCTs suitable for different regions must be advocated only for those regions for their better performance, viz., direct seeding of rice grains successful only in medium- to heavy-textured soils, etc. Similarly, only fresh beds perform better, as old ones reported with higher bulk density and thereby lesser hydraulic properties and finally, yields.
3. Soil moisture dynamics of the RWCS should be worked out with intervening period as a whole instead of focusing on a sole crop as sometimes water saved under one RCT will result in higher water demand in the next crop.
4. Water-stressed regions must be advocated for the cultivars which have shorter stay in field and right time of paddy seedling shifting in field as these do not cutoff the drainage loss as the case with the other RCTs.
5. Happy seeder wheat sowing in standing rice stubbles must be popularized in between the farmers as this improves the SOC, reduces emissions of GHGs, and saves pre-sowing irrigation, thereby cutting down the water, energy, and C footprints of the region.
6. Zero tillage rather double zero tillage must be promoted but with invention of proper herbicides/weedicides to control the weeds.
7. More and more demonstrations pertaining to different RCTs must be carried out at the farmer's field for having their long-term impact on the wider area for the successful and sustainable adoption of the RCTs in the region.
8. Supporting policies from the government sector regarding linking of villages with markets by good roads, proper irrigation facilities, availability of costly machines, viz., Happy seeder, laser leveler, etc., on cooperative basis, proper storage of farmer's produce, and hence overall improving the soil health must be there but in a farmer-friendly mode by respecting their indigenous technologies.

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Agricultural Input Use Efficiency and Climate Change: Ways to Improve the Environment and Food Security

2

P. K. Kingra and A. K. Misra

Abstract

Crop yields and input use efficiency are highly affected by prevailing climatic conditions. Increase in climatic aberrations in the recent past has increased year-to-year variations in crop productivity over different regions of the globe. Crops yield is the maximum under specific set of climatic conditions, referred to as cardinal/optimum limits as under optimum conditions, there is highest growth, yield, and efficiency of utilization of resources. However, increased variations in the recent years are leading to deterioration of soil and environmental health. As a result, input use efficiency is declining, endangering sustainability of agriculture and natural resources and threatening food security. Climate change triggered increase in frequency and intensity of extreme weather events, resulting in significant yield losses every year along with deterioration of natural resources. Climate projections are further indicating about intense warming scenarios if appropriate measures are not taken to contain the emissions from various sectors. Unfavorable weather conditions significantly reduce heat, water, radiation as well as nutrient use efficiency of crops. Under such conditions, adoption of mitigation and adaptation strategies is essentially required to sustain crop productivity and natural resource base. Various agronomic management strategies such as adjustment of sowing time, irrigation management, fertilizer management, etc., need to be adopted in different crops for improved resilience to climate. Identification and

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development of stress tolerant genetic resource base are required to develop varieties able to resist different types of stresses. Various microclimatic modifications such as mulch applications, row orientation, row spacing, etc., should be explored to create optimum crop microclimate. Timely available and accurate weather forecasts and agro-advisory services can also play significant role in decreasing the harmful effects of extreme weather conditions. Crop simulation modeling is another strategy that can be used successfully to study crop responses to various stresses, which can also help in decision-making and research reorientation in view of climate change. The emerging techniques of remote sensing should also be applied in the field of agriculture to monitor and predict crop responses to various stresses and to find out viable solutions at regional level. Multidisciplinary approach involving exhaustive research efforts is the need of the hour for sustaining agricultural productivity as well as improving input use efficiency and environmental health under changing climatic scenarios.

Keywords

Agriculture · Climate change · Environment · Food security · Input use efficiency

Abbreviations

AET	Actual evapotranspiration
ASW	Available soil water
AwiFS	Advanced wide field sensor
B2A	Different climate change scenarios
CERES	Crop
CWP	Crop water productivity
DSSAT	Decision support system for agrotechnology transfer
ET	Evapotranspiration
f	Fractional PAR interception
FACE	Free air CO_2 enrichment
FAO	Food and Agriculture Organization
FYM	Farmyard manure
GHGs	Greenhouse gases
GI	Green index
GIS	Geographic Information System
gLAI	ground measured leaf area index
GPS	Global positioning system
HI	Harvest Index
HUE	Heat use efficiency
IGP	Indo-gangetic plains
IMD	India Meteorological Department
IPCC	Inter-governmental Panel on Climate Change

IRSS	Indian Remote Sensing Satellite
ITSGB	Irrigation at tillering, stem elongation, booting and grain filling stages
IW/CPE	Irrigation water/cumulative pan evaporation
k	Canopy extinction coefficient
K_y	Yield response factor
LAI	Leaf area index
LSD	Least square difference
NCP	North China Plain
NDMI	Normalized difference matter index
NDVI	Normalized difference vegetation index
NDWI	Normalized difference water index
NOAA	National Oceanic and Atmospheric Administration
NUE	Nitrogen use efficiency
PAR	Photosynthetically active radiation
PET	Potential evapotranspiration
PSO	Particle swarm optimization
RMSE	Root mean square error
RRMSE	Relative root mean square error
RUE	Radiation use efficiency
RUEGY	Radiation use efficiency for grain yield
RVI	Ratio vegetation index
SAVI	Soil-adjusted vegetation index
SDD	Stress degree days
SNP	Sodium Nitroprusside
SSP	Shared socioeconomic pathway
$T_c - T_a$	Canopy minus air temperature
T_c	Canopy temperature
TFs	Transcription factors
TSMC	Tarafeni south main canal
WP_{ET}	Water productivity based on evapotranspiration
WUE	Water use efficiency
WUEDM	Water use efficiency for dry matter
WUEY	Water use efficiency for yield
WUE_{YRS}	Remote sensing generated yield-based water use efficiency
Y_{RS}	Remote sensing based yield

2.1 Introduction

Climate is the most important input factor for agriculture. Different crops require specific ranges of climatic parameters at various phenophases, called cardinal limits. Climatic parameters within these ranges during crop growing period lead to bumper yields. However, any deviations from optimum may significantly decline crop productivity. During the recent decades, global warming as a result of anthropogenic greenhouse effect has lead to variations in climatic patterns and accelerated intensity of extreme weather events, leading to adverse effects on agricultural productivity (Kingra and Singh 2016). It has also been observed that developing countries are more vulnerable to climate change, where agriculture typically plays a larger role in national economy (Majumder et al. 2016; Kumar et al. 2018a, b).

South Asian region is highly vulnerable to the impacts of climate change (Bandara and Cai 2014), as more than 30% of the one billion food-insecure people at the globe are living in South Asian region (Sivakumar and Stefanski 2010; Kumar and Meena 2020). Climate change is likely to severely impact food security by the middle of the twenty-first century, with the greatest effect in South Asia (IPCC 2014). Receding of glaciers in the Himalayas and enhanced variability in the monsoon rainfall along with frequency and intensity of extreme weather events have further increased the vulnerability of population of South Asia to climate change (Krishnan et al. 2019; Sivakumar and Stefanski 2010).

Future projections of climate change impacts on agriculture indicate large uncertainty, which complicates strategies for proactive management and planning (Gourdji et al. 2015; Challinor et al. 2009; Hoffman and Rath 2013; Koehler et al. 2013; Vermeulen et al. 2013). Singh (2009) has estimated significant reduction in wheat production in India by 2070 due to climate change. Boomiraj et al. (2009) have observed decrease in yield of irrigated mustard to the tune of 60% by 2080 in the Indo-gangetic plains. Lal (1998) have reported 3.16 and 13.72% reduction in potato production by 2020 and 2050 under Indian conditions. However, the reduction in yield with increase in temperature is expected globally. Lobell and Burke (2008) also observed negative correlation of wheat yield with temperature and positive correlation with rainfall.

As the tropical and subtropical regions are already exposed to higher temperatures, further increase can have adverse impacts on crop productivity over these regions. Increase in temperature in these areas might lead to reduction in crop yields even under elevated CO_2 levels. Although the effect of rise in temperature by 1 °C can be counterbalanced by increase in concentration of CO_2 up to about 600 ppm, further rise in temperature will certainly have adverse impact on crop productivity (Kingra and Singh 2016; Meena et al. 2020). Under such conditions, appropriate mitigation/adaptation strategies are required to maintain agricultural sustainability and enhanced crop productivity along with improved input use efficiency.

2.2 Climate Change and Variability

The composite of long-term weather conditions of a place is referred as the climate of that place and variability is a major aspect of it. This change in the climate results due to the long-term changes in the weather patterns such as temperature or rainfall. Although this may be the consequence of natural internal processes of the climate system (e.g., volcanic eruptions, variations in the Sun's output, Milankovitch Cycles or the natural variations in concentrations of CO_2 and other greenhouse gases), currently climate change is mainly attributed to the anthropogenic external factors. As major cause of climate change and global warming from last many decades is attributed to anthropogenic activities.

"Climate variability" refers to the deviations of climate data at a certain time (such as month, season, or year) compared to long-term data for the same calendar period, commonly called anomalies, while climate change refers to long-term changes in climatic parameters occurring over decades, centuries, or longer.

2.2.1 Observed Climatic Trends

The earth's climate has witnessed abrupt changes in last few decades, which are evident from a wide range of ground and satellite observations. Although there are some natural causes of the increase in temperature of the earth, it can be clearly seen that the recent accelerated warming of the earth is primarily due to anthropogenic activities. India has witnessed a rapid increase in its mean temperature, which is increasing at the rate of 0.61 °C/100 years (Fig. 2.1). However, it can be clearly observed that this rate has been increased considerably in previous couple of decades, which could be attributed to the climatic forcing due to anthropogenic activities and changing patterns of the land use and land cover.

Similarly, Kingra et al. (2017) observed a significant increase in minimum temperature in different agroclimatic zones of Punjab. On an average, minimum temperature has been observed to increase at about 0.05 °C per year during both *kharif* and *rabi* seasons (Table 2.1). Whereas maximum temperature during rabi season has been observed to increase in northeast (@ 0.034 °C/year) and central

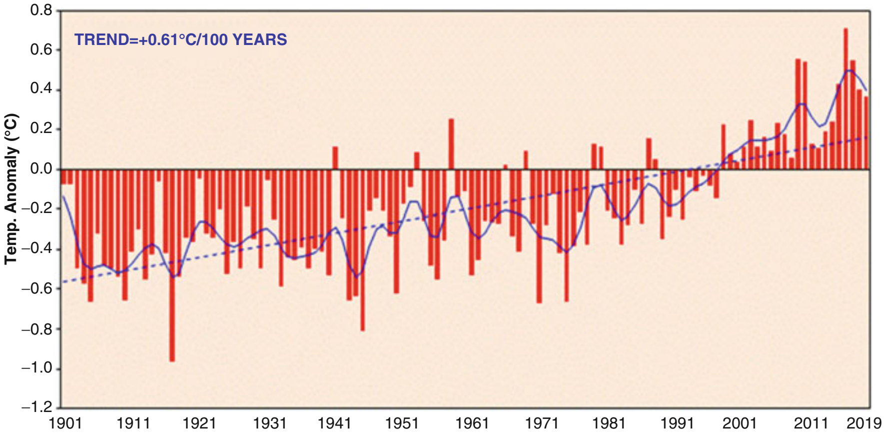


Fig. 2.1 Annual average land surface air temperature anomalies over India for the period 1901–2019 (Anomalies computed with respect to the base period of 1981–2010). Source: IMD (https://mausam.imd.gov.in/imd_latest/contents/cs_anomaly_timeseries_temp_rainfall.php).

Table 2.1 Variability and trends in long-term (1974–1975 to 2013–2014) temperature and precipitation during *kharif* and *rabi* seasons in different agroclimatic regions of Punjab (Kingra et al. 2017)

Region	Test	T_{max} (°C)	T_{min} (°C)	RF (mm)
Kharif season (May–October)				
Northeast	Mean ± SD	32.8 ± 0.2	21.5 ± 0.8	790 ± 52.2
	Z	0.478	4.509***	0.664
	Q	0.005	0.044	0.194
Central	Mean ± SD	34.9 ± 0.7	22.8 ± 0.5	581 ± 120.1
	Z	0.000	5.604***	0.944
	Q	0.000	0.051	0.408
Southwest	Mean ± SD	35.9 ± 0.1	23.4 ± 0.2	306 ± 119
	Z	−1.596	5.138***	0.618
	Q	−0.015	0.047	0.261
Rabi season (November – April)				
Northeast	Mean ± SD	23.2 ± 0.6	9.1 + 0.2	173 ± 79.3
	Z	2.645**	4.742***	−1.130
	Q	0.034	0.052	−0.193
Central	Mean ± SD	24.7 ± 0.7	9.7 + 0.6	121 ± 33.3
	Z	2.086*	4.276***	−1.247
	Q	0.022	0.046	−0.130
Southwest	Mean ± SD	25.9 ± 1.0	10.0 + 0.3	67.1 ± 5.5
	Z	−1.456	4.602***	−0.711
	Q	−0.019	0.047	−0.058

Z: Mann-Kendall test, Q: Sen's slope estimator; * Statistically significant trends at the 5% significance level, ** Statistically significant trends at the 1% significance level, *** Statistically significant trends at the 0.1% significance level

(@ 0.022 °C/year) regions. However, no significant change was observed in rainfall indicating its highly erratic pattern.

2.2.2 Future Climate Projections

There has been 1.0 °C of global warming above pre-industrial levels with very high possibility that it may reach to 1.5 °C between 2030 and 2052 in case, no suitable measures have been adopted to reduce the dependency on GHGs (IPCC 2018). The annual mean temperature over South Asia is projected to increase by 1.2 (0.7–2.1) °C, 2.1 (1.5–3.3) °C, and 4.3 (3.2–6.6) °C under the low-, medium-, and high-forcing scenarios, respectively, by the end of this century as compared to the present (1995–2014) climate. The country-wise average annual is projected to increase by 17.1% in Bangladesh, 18.9% in Bhutan, 27.3% in India, 19.5% in Nepal, 26.4% in Pakistan, and 25.1% in Sri Lanka by the end of this century under (Almazroui et al. 2020).

Various climatic models have predicted that the persistent anthropogenic climate change induced global warming beyond the next century. In case of unrelenting emission of greenhouse gases (GHG) at current rate, the global temperature may increase by approximately 5 °C by the end of twenty-first century. Although the rise in the temperature at various places of the globe is not expected to be homogeneous, some places may witness much higher increase in temperature as compared to other places. Such kind of changes may greatly alter the climate system of several places by changing the rainfall patterns. These changes may also adversely affect the flora and fauna of any place, and agricultural activities will be severely affected by these changes.

It has also been estimated that the mean temperature over India may rise by about 4.4 °C by the end of this century under RCP 8.5 scenario. Moreover, the events of extreme weather such as warm days and nights are anticipated to amplify by 55% and 70%, respectively, relative to the period of 1976–2005, although their impacts are expected to be more prominent in the Indo-Gangetic plains of India, which play a major role for agricultural crop production (Krishnan et al. 2020). Similarly, annual maximum and minimum temperature in Punjab are expected to increase by 2–3 °C by 2020–2050 (Jalota and Kaur 2013).

2.3 Crop Response to Climate Change

Crop production is very sensitive to changes in prevailing weather activities, hence climate change has a direct role on the biophysical aspects of agricultural production (Nelson et al. 2014; Kumar et al. 2021). It can play a decisive role in agricultural production by altering several activities, e.g., changes in average temperature, amount of rainfall and its distribution, extreme weather events such as hot and cold waves, CO_2 concentration and increase in sea level, etc. Increase in climatic variations and extreme weather events in the recent past have exerted significant effect on crop productivity over different regions on earth. Such aberrations and their adverse effect on agriculture cannot be overruled in the years to come, rather it is expected to increase in future, which necessitates the need to understand their impact on crop productivity so that viable management options can be explored to sustain crop productivity and food security in future (Kingra et al. 2019a, b, c).

Global warming scenarios are proving detrimental for crop production. The state of Punjab is already experiencing climatic variability and limiting water availability conditions leading to thermal and water stress in agriculture. In addition to this, excessive use of fertilizers in the state is responsible for large emission of greenhouse gases from agriculture along with increase in the cost of production.

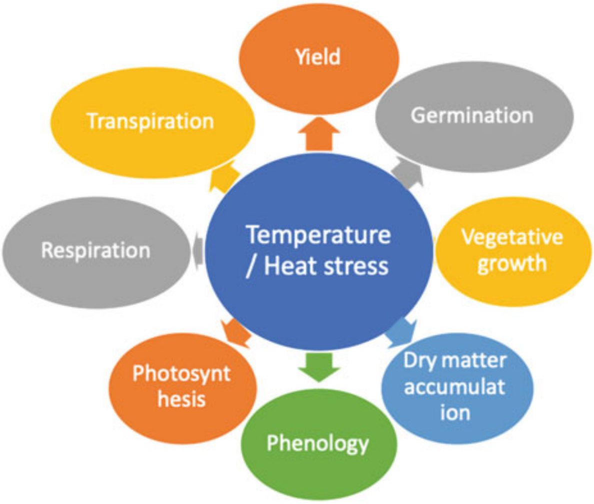
Zhao et al. (2017) reported decrease in the yields of major staple food crops globally such as wheat, rice, maize, and soybean by 6.0, 3.2, 7.4, and 3.1%, respectively, with 1 °C rise in global mean temperature. However, these changes will be highly heterogeneous across crops and geographical extents. Since the quantum of change in the average temperature is expected to be much higher in magnitude, climate change becomes a major threat to the global food security in coming decades.

2.3.1 Effect of Temperature/Heat Stress

Heat stress is the most important abiotic stress reducing the crop production considerably and threatening global food security (Lamaoui et al. 2018). The rising temperature limits the growth and metabolism, leading to significant loss of yield potential of various crops (Kaushal et al. 2016). The direct links between climate change and heat events have been well established (Luber and McGeehin 2008). Increase in temperature results in the enhanced heat stress on the crops (AghaKouchak et al. 2014; Fischer and Knutti 2015; Sun et al. 2019) (Fig. 2.2). Heat stress severely affects the rate of photosynthesis, dry matter production, vegetative growth, development and yield (Nadeem et al. 2018). Increase in minimum temperature has more adverse impact on wheat productivity as compared to maximum temperature. Climatic warming results in enhanced maturity, decrease in grain filling period, and hence, reduction in wheat productivity (Kingra et al. 2019a, b, c).

For every plant species, there is a defined temperature range termed as cardinal temperature. The temperature beyond the cardinal points at critical growth stages may have detrimental effects on the plants. The response of temperature varies from one crop/variety to another and also gets changed at different crop growth stages (Hatfield and Prueger 2015). Moreover, there are several crop phenological stages which are highly sensitive to temperature changes. For example, reproductive stage of maize (Hussain et al. 2019), flowering and grain-filling stages in rice (Cheabu et al. 2018).

Fig. 2.2 Adverse effect of heat stress on crops



Enhancement in temperature also decreases the duration to crop maturity which results in the decrease of yield as crop gets less time for grain filling resulting in the abortion of grains and sterility (Barlow et al. 2015; Hatfield and Prueger 2015). In addition to this, prolonged heat stress can result in sun burn, scorching of branches and leaves, over-harvesting of fruits, and leaves along with discoloration and growth reduction (Fahad et al. 2017). It has been observed that lower nighttime temperature during the reproductive growth period of wheat has been found favorable for attaining higher grain yield of wheat under central Punjab conditions (Kingra 2016).

Kingra et al. (2010) developed regression models to forecast wheat yield from canopy temperature and observed significantly negative relationship of grain yield with various canopy temperature-based indices and depicted their ample scope to evaluate plant water status and predict grain yield. Kaur et al. (2016) also observed negative relation of canopy temperature and stress degree days with grain yield. Asseng et al. (2011) also reported decline in grain production of up to 50% when temperature was higher than 34 °C due to variation in average growing season temperature of ±2 °C.

Lobell et al. (2012) stated that wheat yield in India is more prone to short-term weather extremes in which heat stress is foremost factor responsible for low yield especially when it occurs during anthesis and grain filling stages. Augmented average temperature influences the crop and senescence gets accelerated due to heat extremes. Pal et al. (2012) revealed that the grain yield, biological yield, and straw yield decreased as sowing was delayed by about 3–4 weeks. Delay in sowing reduced number of tillers as it exposed the crop to higher temperature during reproductive stage, which reduced the length of growing season thus reducing the wheat yield.

Mohanty et al. (2015) also reported negative relation of wheat yield with temperature and positive with CO_2. Rao et al. (1999) revealed nighttime temperature during post-anthesis period to be the foremost factor affecting wheat yield with reduction of 7% (204 kg/ha) with 1 °C rise in nighttime temperature. The major thermal constraints for attaining high productivity were maximum and minimum temperature. Gupta et al. (2010) observed highly detrimental sudden rise in temperature in March in the Indo-Gangetic Plains (IGP). Xiao et al. (2012) also reported enhanced maturity of winter wheat due to climate warming in the North China Plain during the period 1981–2009. Samra et al. (2012) reported increase in wheat yield by 356 kg/ha (7.4%) during a cold wave year and reduction of 217 kg/ha (4.5%) during a heat wave year.

2.3.2 Effect of Rainfall/Water Stress

Apart from increase in temperature, climate change is also expected to disrupt the distribution and intensity of rainfall events, which may result in the more frequent extreme weather events (Allan 2011; Min et al. 2011; Westra et al. 2014) that may bring into more number of flood and drought events with increased intensity (Guhathakurta et al. 2011; Minakawa and Masumoto 2013; Mishra 2014; Soltani et al. 2020; Zhu 2013). Increase in sea level and glacier melting is another major challenge caused by the climate-change-led global warming. The accessibility to quality drinking water is also project to affect the millions with major impacts on the low-income population from the developing nations.

Variability in precipitation directly affects droughts and floods resulting in detrimental consequences (Ebi and Bowen 2016). Direct and indirect losses resulting from floods are continuously rising in India due to the country's large and dense population base. Floods are known to cause major losses to household items, machineries, transport, storage, etc. In agriculture, they create the problem of water logging and soil erosion, etc., which results in partial or complete loss of agricultural produce. Livestock sector also gets badly affected due to the floods.

Water logging reduces the availability of oxygen to the plant roots which causes less root respiration and may result in the reduction of the cell permeability or even complete death of root cells (Brisson et al. 2002). It also creates loss of nitrogen to the soil through the process of denitrification, nitrate leaching, and runoff in addition to the soil nitrogen mineralization (Kaur et al. 2020).

Drought has become a very common but serious phenomenon, and it is very complex to predict its onset date since it develops slowly and gradually without much visible signs in its initial stage. Agricultural sector alone has about a whopping 83% contribution among the total losses due to drought and the worst sufferers are crop and livestock sectors (FAO 2018). Using a 44 years data (1964–2007), it has been observed that droughts and extreme heat lead to about 10% reduction in the cereal production globally (Lesk et al. 2016).

Drought stress alters the basic morphology, physiology, and biochemical characters of the plant, and thus it becomes imperative to recognize it in its advance stage (Iqbal et al. 2020). Drought events lead to a prolonged water loss and excessive heat stress for the plants, which can reduce their yields if they occurred during certain important crop-growth stages such as reproductive stage of rice (Yang et al. 2019), booting and grain filling stages of wheat (Ihsan et al. 2016; Mishra and Tripathi 2010), seedling and jointing stages of maize (Effendi et al. 2019) and grain filling to grain maturity for barley (Samarah 2005), etc.

Water stress is said to occur when demand exceeds the amount of water available at a certain period of time, and also when deterioration of quality restricts its usage. Plants show symptoms of water stress either due to limited water supply to their roots or due to excessive loss of water through transpiration. The most important factors for water stress in plants are rainfall, water retaining capacity of soil, and loss of water through evapotranspiration (ET). Kaur et al. (2016) observed significant effect of daytime temperature on PET of *kharif* maize.

The water stress in the plants adversely affects their growth and developmental activities, translocation of water and nutrient, photosynthesis, and partitioning of assimilates (Fahad et al. 2017). Response of varieties to drought stress varies with plant species and is also governed by the plant growth stages and surrounding meteorological conditions (Demirevska et al. 2009). Drought also affects the interception of the photosynthetically active radiation by the plants and its utilization efficiency (Mishra et al. 2009), which in turn results into the suppressed growth and lesser yields characters (Earl and Davis 2003; Hao et al. 2016).

Kattge and Knorr (2007) reported significant effect of temperature and rainfall on phonological, stomatal conductance, crop yield, and water use efficiency (WUE). Ali (2009) investigated that the yield response factor (k_y) of semi-dwarf winter wheat varied with crop growth stage and among seasons. Akram (2011) also observed higher yield and yield attributes of wheat with rise in relative water content, whereas water stress at tillering and anthesis caused rigorous decline in yield.

2.3.3 Effect of Solar Radiation

Quality, intensity, and duration are most important in light. Maximum photosynthesis occurs in red and blue light whereas green light is reflected by plants (Kingra et al. 2019a, b, c). Majority of plants flower only when they are exposed to specific day length which is called as photoperiod (Dhaliwal and Kler 1995). Low sunshine hours during reproductive period lead to significant reduction in crop yield. For getting higher yield, solar radiation of 300 cal/m^2/day is appropriate. However, lower daily average temperature and higher solar radiation during maturity are favorable for obtaining better yield (Pillai and Nair 2010). Kingra (2016) reported that rise in nighttime temperature and reduction in sunshine hours had negative impact on rice productivity in central Punjab.

Mahi (1996) reported increase in yield of wheat by 7% and rice by 13% with increase in solar radiation up to 10%, but grain yield declined under decreasing amount of solar radiation. Baker et al. (1994) observed significant reduction in dry matter production and yield of rice with decrease in light and increase in high thermal stress. Vijayalakshmi et al. (2008) found decrease in the total biomass and yield of rice under light stress as it increased the number of ill-filled spikelets.

Kaur et al. (2016) reported that 5% decrease in solar radiation causes decline in wheat yield by 3.8% from normal. Similarly, increase in 5% of solar radiation would increase yield by 3.6%. The interactive effect of doubling CO_2 concentration (600 ppm) and increase in temperature by 2 °C increase the grain yield by 5.6% from normal but this positive effect of CO_2 over-increasing temperature was seen up to some degree. The simulated maximum biomass yield, leaf area index, and grain yield were decreased by 18.4 to 29.2%, 13.7 to 22.9%, and 9.8 to 18.0%, respectively, from normal when the temperature was increased by 1.0 to 2.0 °C, but they increased with decrease in temperature.

2.3.4 Effect of CO_2

Carbon dioxide is the most important greenhouse gas. Although the global warming potential of CO_2 is much less as compared to other gases, viz., methane (CH_4) and nitrous oxide (N_2O), it alone contributes for about 65% of total greenhouse gas emissions on a global scale (IPCC 2014). Its concentration has increased from the

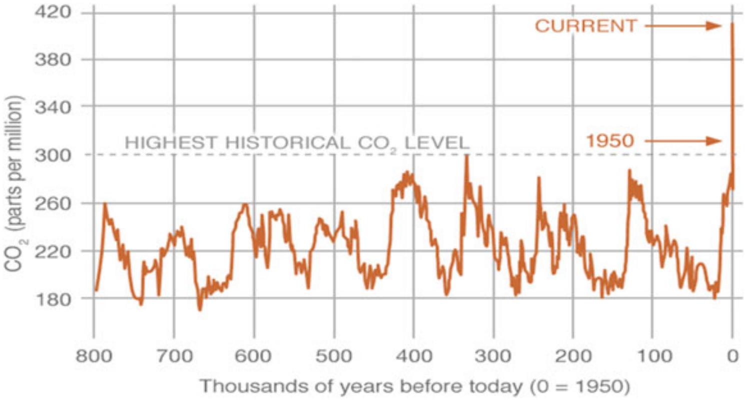


Fig. 2.3 The record of atmospheric CO_2 over the last 800,000 years based on data from NOAA NCEI Paleoclimatology data (NOAA 2020)

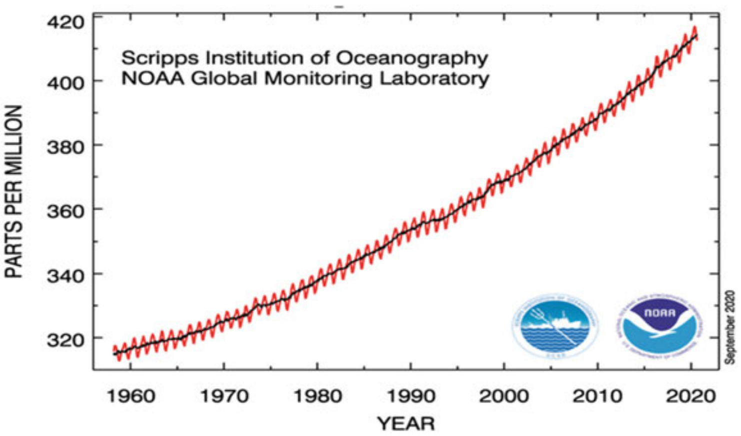


Fig. 2.4 Variation in the atmospheric CO_2 concentration at Mauna Loa Observatory, Hawaii (Tans and Keeling 2020)

pre-industrial era of about 284.7 ppm in 1850 (Wang and Nemani 2016) to 409.8 ppm in 2019 (Tans and Keeling 2020). Although there has been natural fluctuations in the carbon dioxide concentrations due to natural causes, it has never crossed the level of 300 pm (Fig. 2.3) (NOAA 2020). However, in the recent times, increase in annual CO_2 during past 60 years is as high as about 100 times of the previous natural increase (Lindsey 2020) and it is continuously increasing (Fig. 2.4).

Apart from this, CO_2 is essential for photosynthetic activities in the plants. It is also a source of all the carbon in organic matter which includes the plants, animals, fungi, bacteria including human being (Chaloner 2003). In general, elevated CO_2

Table 2.2 Effect of increase in CO_2 concentration on plant growth

Process	Effect of increase in CO_2 concentration	Remarks
Photosynthesis	Increase	C_3 plants: 30–50% C_4 and CAM plants: 5–15%
Respiration	Increase	Increase in canopy temperature under elevated CO_2
Stomatal conductance	Decrease	Direct effect
Organ growth	Increase	Increase in assimilation
Transpiration (per unit leaf area)	Decrease	Reduction in stomatal conductance
Water uptake	Decrease	Decrease in stomatal conductance and transpiration
Water use efficiency	Increase	Reduction in transpiration
Nitrogen concentration in biomass	Decrease	Increase in biomass
Nitrogen uptake	Increase	Increase in nitrogen demand

Source: Tubiello and Ewert (2002) and Kingra and Singh (2016)

concentration results in enhanced photosynthesis in the plants (Sengupta and Sharma 1993; Taub 2010), which ultimately results in enhanced plant growth and grain yield for majority of the plants (Madhu and Hatfeld 2013; Thompson et al. 2017). These responses are more prominent in C_3 plants as compared to C_4 plants due to the difference in their mechanism of CO_2 use.

Elevated CO_2 affects the crop growth mainly in two ways. First, by increasing net photosynthesis and second, by reducing stomatal conductance hence decreasing rate of transpiration (Farquhar et al. 1978). On an average, doubling of CO_2 concentration can reduce stomatal conductance by about 20% (Drake et al. 1997). Wheat crop suffering from water stress is more responsive to increase in CO_2 (Sionit et al. 1980). Due to fertilization effect of CO_2, more vigorous plants and higher yields are obtained (Acock and Acock 1993).

Plant photosynthesis is highly responsive to CO_2 concentration (Dahlman 1993). But this response is slower in C_4 plants than C_3 (Allen 1990; Brouder and Volenec 2008). As increased CO_2 concentrations lead to reduction in transpiration, it can improve water productivity (Rosenberg et al. 1990). Singh et al. (1990) observed significant variations in water potential under water stress in different wheat genotypes. Thus, coinciding biomass production with periods of lowest atmospheric demand can prove advantageous (Gupta 1995) (Table 2.2).

2.3.5 Effect of Nutrient Stress

Nutrient stress has adverse impact on crop growth, yield, and quality (Morgan and Connolly 2013). Asseng et al. (2004) observed increase in yield with increase in CO_2 in the dry and high N treatments, but little or no response was observed in the wet and low N treatments. Ali et al. (2003) also observed higher plant height, yield, and yield attributes of wheat with increase in nitrogen application.

Bundy and Andraski (2004) reported that maximum number of spikes m^{-2} were recorded with 2% potassium nitrate followed by sodium nitroprusside (SNP) 400 μg/mL and thiourea 20 mM, compared to untreated control to the extent of 11.87, 10.9, and 9.4%, respectively. This might be due to reduced flower and immature grain drop, prevention of development of abscission layer, which resulted in the formation of more spikes and their retention on plants and produced significantly higher number of grains/spike than untreated control. SNP can protect cell membrane and maintain their structure and function against the toxic and destructive effects of reactive oxygen species during the stress. This, in turn, can lead to more absorption and translocation of minerals from the soil to the plants and, thereby, formation of more grains spike^{-1}.

Sahu et al. (2006) observed significant improvement in growth with the application of thio-urea in wheat. Tian and Lei (2006) reported that potassium (K) is essential for enzyme activation, protein synthesis, and photosynthesis, and it may act as osmo-regulator during stress for increased active update of K^+ by the guard cells and stomatal regulation. Potassium (K) plays an important role in carbohydrate formation, maintains water balance in leaves and regulates stomata closing, which have direct effect on plant stress resistance and its water use efficiency. Meshah (2009) reported its positive effect on stress resistance and water use efficiency of wheat as a result of maximum yield attributes and grain yield. Schierhorn et al. (2014) reported the annual yield potentials for both rainfed and irrigated conditions from 1995 to 2006 with most favorable nitrogen supplies.

2.4 Climate Change and Input Use Efficiency of Crops

As all the plant physiological processes are significantly affected by climatic parameters, changing climatic parameters are likely to have severe implications of all these growth processes, hence, adversely hitting input use efficiency in agriculture.

2.4.1 Heat Use Efficiency

Heat use efficiency indicates the heat utilization to produce unit plant biomass. It is calculated from temperature-based agrometeorological indices called growing degree days and is also referred to as thermal use efficiency. Heat use efficiency (HUE) mainly depends on crop genetic and management factors (Rao et al. 1999). As the crop response is highly affected by climatic parameters, heat use efficiency is also affected by climatic variations during crop season. Kingra and Kaur (2012, 2013) observed that earlier sown crop *Brassica* sp. recorded higher heat use efficiency during all the crop-growing seasons.

Amrawat et al. (2013) also observed better performance of wheat when sown earlier. Kaur et al. (2019) reported that sowing of maize crop during second week of June with irrigation of IW: CPE 0.75 under mulch application has been found to be the most efficient for heat utilization.

Kaur et al. (2016) also observed reduction in heat use efficiency (HUE) of wheat with delay in sowing. Jhanji and Gill (2011) and Pandey et al. (2010) also reported significant decrease in heat use efficiency with delay in sowing. Kingra et al. (2011) reported that water stress induced increase in temperature accelerated the crop maturity and shortened the period of growth and reduced crop yield. Heat use efficiency decreased in water-stressed crop.

Ottman et al. (2012) observed decline in grain yield with increase in temperature. Mohammad et al. (2014) observed accelerated maturity and reduced yield under elevated growth temperature (25 °C) in comparison to ambient temperature (15 °C). Dhillon et al. (2017) also reported the descending order of heat use efficiency of sunflower with each successive delay in sowing.

2.4.2 Radiation Use Efficiency

Radiation use efficiency is a very important parameter for quantification of biomass accumulation. Generally, higher RUE is observed with increase in diffused radiation (Sinclair et al. 1992). Greaves and Wang (2017) have reported reduction in radiation interception and its use efficiency under reduced biomass. Radiation interception is further affected by the amount and quality of incident radiation, leaf area index, the distribution of which in canopy architecture is accounted for by the extinction coefficient. The HI is highly species-dependent, as a result, the major genetic yield improvements in the past have been conducted by improving the HI in most of the cereal crops (Sadras et al. 2016).

Caviglia and Sadras (2001) reported that reduced WUE as a result of reduction in nitrogen occurs due to proportionally greater reduction in RUE than the decrease in conductance. Connell et al. (2004) concluded that seasonal conditions had minimal impact on extinction coefficient and RUE. Li et al. (2008) recommended that furrow planting combined with deficit irrigation is helpful in improving the RUE and grain yield of winter wheat. Ram et al. (2012) reported lower grain yield in delayed sowing as a result of reduced number of days taken to attain different phenological stages, which reduced radiation use efficiency (RUE) and yield attributing characteristics. Singh et al. (2017) also observed higher PAR interception and radiation use efficiency in earlier sown brassica crop.

Mubeen et al. (2013) reported the significant effect of climate and weather conditions on yield and resource use efficiency of wheat at Faisalabad. Hossain et al. (2014) observed positive correlation of radiation use efficiency (RUE) of maize with leaf area index (LAI) and incident radiation, but negative with water stress.

2.4.3 Water Use Efficiency

Changing climate parameters are likely to have significant effects on WUE. Kingra et al. (2019a, c) assessed actual evapotranspiration (AET) and water productivity (WP_{ET}) of rice and wheat in relation to changing climatic conditions over a period of 32–46 years for three locations, viz., Ballowal Saunkhari, Ludhiana, and Bathinda. A large variation in AET of rice and wheat was observed over the years with increasing trend at Ballowal Saunkhari and decreasing trend at Ludhiana and Bathinda. This resulted in significant increasing trends in water productivity of both wheat and rice at all the stations. The water productivity of rice was negatively correlated with AET while water productivity of wheat had curvilinear relationship with AET.

Tubiello et al. (2000) recommended the adoption of short-term adjustments at the field level to manage crop water use efficiency. Various management practices, viz., nutrient management, adjustment in sowing time, and choice of species or cultivars, can contribute significantly (Asseng et al. 2001).

Tanner and Sinclair (1983) reported strong influence of weather conditions on water use efficiency (WUE) of wheat. Ritchie (1991) reported that the models of moderate complexity can accurately predict the duration stages of plant growth, water balance, plant biomass accumulation rates, and partitioning of biomass to the economic yield under limiting water conditions. Hassan et al. (2000) also observed highest wheat yield with irrigation at two stages, viz., grain formation and ripening stages along with about 34% of irrigation water saving as compared to normal watering.

Guo et al. (2010) reported increase in wheat yield and water use efficiency by 38 and 40% with increase in CO_2 concentration to 600 ppm over the North China Plain. Bandyopadhay (1997) reported that irrigation of 50 mm applied at 1.2 IW: CPE gave the maximum yield and yield attributes and showed highest water use efficiency and actual evaporation. Water uptake was found maximum from 0 to 15 cm layer and it gradually changed with the soil depth.

Kang et al. (2002) showed high dependence of grain yield, biomass, water use efficiency (WUE), and harvest index depended on soil moisture content in winter wheat. Panda et al. (2003) proposed that only 0–45 cm of soil layer need to be considered while scheduling irrigation for wheat grown under water scarce conditions. Ilbeyi et al. (2006) reported increase in grain yield by over 65% by using 50 mm of irrigation water at sowing. Liu et al. (2007) noticed 56% higher crop water productivity under the irrigation than rainfed conditions.

Li et al. (2010) reported higher grain yield and WUE with irrigation at the jointing and heading stages in wheat. Li et al. (2010) suggested that the furrow planting pattern facilitates better winter wheat production with evapotranspiration, as grains yield under deficit irrigation. Sun et al. (2006) showed that suitable irrigation schedules must be established to optimize yield and economic benefits. Ram et al. (2012) highlighted the benefit of rice straw mulch to increase yield, soil organic carbon, and water use efficiency in wheat. Ali et al. (2014) suggested a considerable scope of improving irrigation water use efficiency of wheat with appropriate management. Majumder et al. (2016) reported that need-based irrigation scheduling and water application (IW/CPE = 1.00) in combination with subsurface manuring can be helpful in managing crop water productivity in view of limiting water availability and changing climatic scenarios under Punjab conditions.

2.4.4 Nutrient Use Efficiency

Nutrient use efficiency (NUE), referring to the measure of efficiency of utilizing the available mineral nutrients by plants, is estimated as yield (biomass) per unit fertilizer/nutrient content. NUE is affected by many factors, viz., ability of plant to take up the nutrients from the soil, its transportation, storage, mobilization, and use in the plant as well as environment. Enhancing NUE is a major target for crop improvement particularly for enhancing crop production under marginal lands with low nutrient availability as well as to decline the use of inorganic fertilizers (Hawkesford et al. 2014), which can significantly control emissions from agriculture. There is ample scope of continued optimization nutrient application under changed climate (Brouder and Volenec 2008). Mandic et al. (2015) reported that nitrogen agronomic efficiency (NAE) and nitrogen use efficiency (NUE) significantly declined at high N rates.

Shabbir et al. (2015) reported foliar spray of NPK to be efficient in improving wheat growth. Zain et al. (2015) reported substantial increase in growth and yield of wheat with foliar application of micronutrients. Kameai et al. (2016) reported seed inoculation with phosphate bio-fertilizer as effective approach to improve yield and yield components of wheat. Singh et al. (2016) also advocated the foliar spray of micronutrients to manage adverse impacts of warming scenarios.

2.5 Effect of Climate Change on Food and Environmental Security

Undoubtedly, climate change is posing a serious challenge to the food security for the burgeoning population growth on the planet (Kingra 2017; Yadav et al. 2020). To achieve food security for burgeoning population, there is a dire need to increase production of food grains per unit land area. There are many factors which are responsible for year-to-year variations in wheat yield, which include land preparation, sowing time, rate of fertilizer application, irrigation scheduling/frequency and weed management, etc. However, all these factors are greatly influenced by prevailing weather conditions, viz., rainfall received at different crop phenophases, prevailing temperature and moisture, etc. (Malik et al. 2009). As a result, climate variations lead to large annual fluctuations in wheat productivity (Kaur and Behl 2010). Very high temperature at grain filling stage results in the highest loss in crop production (Balla et al. 2009).

Perry and Swaminathan (1992) have predicted decrease in yield in North India by 0.5 tons per hectare with rise in temperature by 0.5 °C along with decrease in its total duration by 7 days due to enhanced plant growth, flowering, and maturity (Rahman et al. 2009). The higher temperature significantly fastens the crop development, thus shortening its growing duration (Zacharias et al. 2010; Hossain et al. 2012). Higher yields were observed when the plants experienced heat stress during early growth as compared to those which experienced it at anthesis (Zhang et al. 2013). Increase in temperature by 1 °C resulted in 8% decrease in wheat grain and biomass yield (Mohanty et al. 2015). Refay (2011) reported that substantial loss in grain yield to the extent of 7.98% when sowing was delayed. The crop sown in November obtained highest spike weight, grain yield, and biological yield. However, late-sown genotypes were observed to have higher protein content, which might be possibly due to less grain weight under late sowing (Sial et al. 2005).

Increased hectoliter weight and grain protein, but decrease in nutrient use efficiency was observed under higher rate of nitrogen application (Campillo et al. 2010). Although the reduction of nitrogen reduced grain yield and NUE, it increased kernel weight (Khalilzadeh et al. 2011). Increase in the concentration of greenhouse gases and warming is expected to increase evaporation and uncertainty in rainfall, which may have great effect on productivity of crops in future (Reddy and Hodges 2000). However, the adverse effects can be counterbalanced by making adjustment in sowing dates of the crops (Kajla et al. 2015).

2.6 Ways to Improve Crop Yield and Input Use Efficiency to Attain Food and Environmental Security

In view of the climatic changes, research goals need to be shifted from enhancing crop productivity towards optimizing input use efficiency to sustain natural resources while attaining food security (Kingra 2017). Short-term adjustments at the farm level (Tubiello et al. 2000; Asseng et al. 2001) as well as long-term adaptations (Eitzinger et al. 2010, Alexandrov et al. 2002) are required to enhance crop yield and input use efficiency (Fig. 2.5). However, Southworth et al. (2002) have predicted increase in wheat yields by 60–100% in the central and northern areas in Midwestern United States, whereas some increases as well as decreases were observed for the southern areas.

Doos and Shaw (1999) concluded that most of the impacts in future crop production are expected as a result of “direct human factors such as improved management”. Poorly managed fields will be more susceptible to losses in warmer years and will be able to increase their production more in cool years (Lobell et al. 2002). Microclimatic modifications help in modifying the adverse conditions prevailing in the immediate vicinity of the plants making it favorable for better crop growth and yield. Artificial control of field microclimate to maintain the optimum conditions for better plant growth and crop production can be achieved by making field level adjustments such as appropriate sowing time, row spacing and orientation, planting method, mulch application, use of shelterbelts/wind breaks and intercropping, etc., and result in the maintenance of favorable crop microclimate by moderating temperature extremes, conserving soil moisture, and increasing radiation

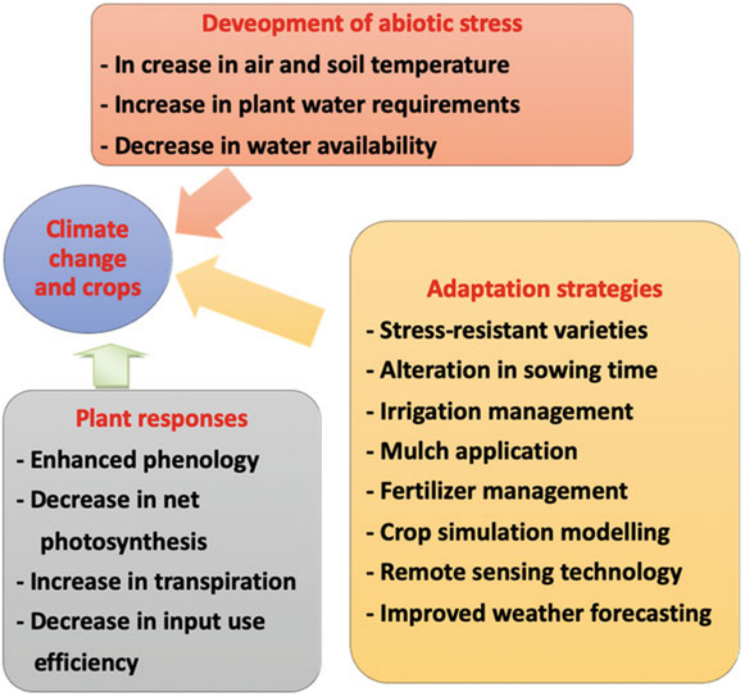


Fig. 2.5 Abiotic stresses, plant responses, and adaptation strategies to address climate change impacts on agriculture

interception (Kingra and Kaur 2017). Rani et al. (2017) also reported that microclimatic modifications such as date of sowing, irrigation management and mulch application, etc., can be highly beneficial for alleviation of heat and water stress under changing climate and water-limiting scenarios in the future.

2.6.1 Developing Stress-Resistant Varieties

Due to climate changes and increase in population in the recent past, increase in incidence of abiotic stresses has decreased crop productivity. Under such conditions, stress-resistant crops might help to ensure yield stability (Zhang et al. 2018). These is dire need for developing stress-resistant varieties by applying transgenic breeding techniques as a suitable alternative to conventional breeding (Anwar and Kim 2020). However, only meager success could be achieved through conventional breeding approaches because of complexity in stress-tolerance traits. Thus, the transgenic approach is being used quite effectively to breed stress-tolerant crops (Verma and Deepti 2016). Kingra et al. (2019a, b, c) also emphasized that various breeding techniques like screening for stress tolerance, conventional breeding techniques as well as molecular and biotechnological strategies need to be incorporated for developing varieties tolerant to various stresses. Singh et al. (2017) also investigated the response of three wheat varieties (HD 2967, WR 544 and HD 2985) to heat stress by growing them under ambient and elevated temperature (1.9 to 3.4 °C more than ambient during crop season) conditions and found HD 2967 and WR 544 to be more suitable to heat stress.

2.6.2 Alteration in Sowing Time

Several studies have reported higher yield in early sowing and a reduction when delayed (Anderson and Smith 1990; Connor et al. 1992; Owiss et al. 1999; Bassu et al. 2009; Bannayan et al. 2013). Singh et al. (2018a, b) reported appropriate sowing time and row orientation to be effective strategies in improving heat use efficiency. Singh et al. (2016) reported earlier sowing of wheat to manage the weather variability impact and thermal heat stress under Punjab conditions. Singh et al. (2016) concluded that timely sowing of wheat improves heat use efficiency, which is essentially required under climate warming scenarios.

Terminal temperature stress during later growth phases of wheat results in enhanced maturity (Mavi and Tupper 2005). Substantial increase in grain yield of wheat can be achieved by sowing the crop at the optimum time which may vary from variety to variety. Heat shock at the end of tillering severely affects photosynthesis and during grain filling it reduces photosynthesis as well as grain growth (Egli 2004; Schapendonk et al. 2007; Yang et al. 2008). Increase in allocation to reproductive organs leads to increase in yield of cereals (Donald and Hamblin 1976). It would be, therefore, appropriate that plants function in such a manner that maximum amount of dry matter goes to the spikes for increasing weight of grain during post-anthesis period, leading to higher grain yield. In the partitioning of dry matter at physiological maturity, the spikes contribute maximum (Tyagi et al. 2004). Date of sowing influences the yield considerably and delays in sowing subject the crop to mature early due to rise in temperature resulting in decreasing the number and size of grains (Parihar and Tripathi 1989). Mcdonald et al. (1983) reported reduction in grain yield of spring cultivars of wheat 6 and 16% % per week's delay in sowing and anthesis at Narrabri, New South Wales.

Stapper and Harris (1989) observed that delay in sowing of wheat resulted in yield decline 4.2% per week after November 1. Thus, early sowing of appropriate cultivars is beneficial in improving wheat yields (Anderson 1992). The heat stress in late-sown crops can reduce the kernel number per year (Gregory and Eastham 1995). In the rainfed regions, deficit irrigation may lead to significant improvement in water use efficiency (Oweis et al. 2000).

Sowing earlier by 10 days resulted in increased higher yields due to modified microclimate (Attri and Rathore 2003). Among three dates of sowing, the highest photosynthetically active radiation (PAR) was captured in October 7 sowing followed by October 17-, and October 27-sown mustard cultivars (Singh et al. 2017). Wajid et al. (2004) observed significant relation between interception of photosynthetically active radiation (PAR) and dry matter production in wheat.

Estrella et al. (2007) reported changes in phenology of winter wheat due to increase in temperature. El-Gizawy (2009) observed highest yield contributing characters and grain yield in mid-November sown wheat crop, whereas early or delayed planting significantly reduced all these traits. Ali et al. (2010) also reported November 10 to 20 as the optimum sowing time for wheat irrespective of varieties. However, Xiao et al. (2012) reported that warming provided additional suitable environment before winter dormancy and led farmers to postpone sowing in the North China Plain.

2.6.3 Irrigation Management

Irrigation management is an important measure to manage terminal heat stress and improve water use efficiency of wheat (Kingra et al. 2019a, b, c). Oweis (1997) observed increase in water use efficiency of rainfed wheat with good management and favorable rains.

Zhang et al. (2005) also reported higher grain yield and WUE if spring wheat under deficit irrigation. Li (2006) reported improving WUE as the most important way to enhance crop production, save water, and protect the environment. Sun et al. (2006) observed higher yields under some water stress at certain stages as compared to that under full irrigation. Li et al. (2007) also reported increase in the water use efficiency and grain yield under deficit irrigation. However, Tari (2016) revealed significant decrease in wheat yield with water deficits imposed at stem elongation and heading stages. Asseng et al. (2004) observed that higher temperatures increased evapotranspiration with low N input, but reduced it with ample N fertilizer.

2.6.4 Mulch Application

The crop yield increases by retaining residue (Campbell et al. 1993). Plastic film mulch significantly reduces water loss through soil evaporation and increases water uptake, water use efficiency and dry matter production. Dhaliwal et al. (2019) observed that soil moisture was 4–5% higher under mulched crop as compared to non-mulched crop, which ultimately resulted in higher soil temperature during early growth stages. Significantly higher grain yield was recorded in mulched crop. Several studies have reported increase in wheat yield, reduced water use, and improved water use efficiency (Ma 1999) with plastic mulch. The research results showed the total water consumption of corn-wheat rotation to be 780 mm and the water use efficiency 1.9 kg m^{-3} if the farmer retained and incorporated all the straw into the soil and added nitrogen fertilizer and animal manures (Zhang et al. 2001).

Wang et al. (2001) reported reduction in soil evaporation by 50% by using wheat straw mulch. Mulching with crop residues during the summer fallow can increase soil water retention (Feng 1999). Sun and Wang (2001) showed the positive effect of plastic film in promoting crop growth during early stages when temperatures are low. Although plastic mulch is usually used to increase soil temperature, it also helps in saving water (Deng et al. 2006). However, Xie et al. (2005) reported higher ET under plastic mulch due to increase of LAI. Jin et al. (2006) found that deep tillage with mulching reduced runoff by 50% and soil erosion by 90%. Reduced tillage with surface mulch reduced evaporation and increased the water retention capacity of soil (Lal et al. 2007). In addition to this, crop residues shade the soil, slow down surface runoff, and increase infiltration (Mulumba and Lal 2008). Zhang et al. (2009) reported mulching to be an important soil management practice to increase soil water storage especially in arid regions. Straw mulch was observed to decrease the water use from 2.1 to 2.9 cm (Ram et al. 2012).

2.6.5 Fertilizer Management

Appropriate amount, time, and method of fertilizer application prove quite beneficial to minimize the effect of climatic stresses on crops. Zain et al. (2015) observed substantial improvement in growth and yield attributes of wheat with foliar application of micronutrients. Kameai et al. (2016) also reported foliar application by Zinc (Z_n) to be more effective on yield and yield components of wheat crop. Singh et al. (2016) reported that foliar spray of potassium nitrate to be highly beneficial to improve the productivity of wheat under high temperature conditions. Kafle et al. (2015) observed higher heat use efficiency of maize under higher farmyard manure (FYM) and nitrogen level. FYM @ 20 t/ha and N-150% resulted in the highest HUE of 2.8 and 3.0 kg/ha/^{o}C days on grain yield basis, whereas, on dry matter basis corresponding values were 8.4 and 8.9, respectively. Amrawat et al. (2013) also reported the application of 120 kg N/ha in wheat registering significant increase in heat use efficiency over 90 kg N/ha.

2.6.6 Crop Simulation Modeling

Crop simulation modeling studies can be of great benefit to evaluate the effect of climate change scenarios on crop productivity, evaluate sensitivity of different regions to these impacts, and explore most effective options for managing climate change impacts (Kingra et al. 2019a, c). Crop simulation model can serve as an agronomic tool to study uncertainties in crop production due to weather variability (Kaur et al. 2013). Eitzinger et al. (2003) used the CERES-wheat model to evaluate soil water balance under four climate scenarios, and reported that the factors affecting soil water balance also influenced sustainable crop production and water resources.

A persistent decrease in the yield was observed in different cultivars with increase in temperature from 3 °C to 5 °C (Attri and Rathore 2003). Luo et al. (2003) predicted increase in wheat yield under all CO_2 levels and observed the drier sites to be more suitable for wheat production but with lower wheat quality. Andarzian et al. (2015) simulated lower wheat yield in early sowing dates (before November 15) than the normal sowing date (e.g., November 15) at the Khuzestan province, Iran as high temperature in early sowing accelerated crop development stages, reduced crop canopy (leaves and tillers), and decreased biomass production which in turn reduced yield.

Pal et al. (2015) demonstrated the use of CERES-Wheat model for decision-making in production of wheat.

Beck et al. (2016) reported that wheat production in Chhattisgarh was influenced by heat stress as a result of delay in sowing. The DSSAT model was used to determine the production potential for different districts, i.e., Raipur, Bilaspur, Jagdalpur, and Ambikapur under three dates of sowing (D_1: 25/11/2013, D_2: 05/12/2013 and D_3: 15/12/2013). Evaluation with simulated data of three dates of sowing at four districts of Chhattisgarh revealed that Ambikapur showed highest grain yield (5128–5042 kg ha^{-1}) followed by Jagdalpur (4559–4258 kg ha^{-1}), Bilaspur (4314–4198 kg ha^{-1}), and Raipur (4358–4046 kg ha^{-1}) under all three dates of sowing. Sowing on December 5 (D_2) lowest in (5246 kg ha^{-1}) was found more suitable period for Ambikapur due to the low temperature and favorable weather conditions. In other stations, D_1 showed higher grain yield followed by D_2 and D_3. The study showed that D_2 had the optimum production potential yield for Kanchan variety for four districts of Chhattisgarh state under normal conditions. Jin et al. (2016) calibrated the AquaCrop model with the use of the particle-swarm optimization (PSO) algorithm to get better yield prediction.

2.6.7 Remote Sensing and Crop Yield Estimation

Kingra et al. (2016) reported that the remote sensing, global positioning system, and geographical information system can significantly contribute to evaluate the impacts of climate change on agriculture at regional scale. Rastogi et al. (2000) investigated the satellite sensor image based model recommended by Price in India (Karnal and Delhi) over two wheat growing locations for crop periods of 1996–1997 and 1997–1998 and revealed that ground predictions of leaf area index were obtainable, indicating a root mean square error of 1.28 and 1.07 and 1.28 for Delhi and Karnal locations, respectively.

Verma et al. (2003) showed that by using the NDVI-based zonal yield models capability for district level wheat yield prediction enhanced considerably. Salazar et al. (2007) evaluated the relevance of remote sensing data in Kansas for predicting yield of winter-wheat and concluded remote sensing to be a valuable tool for prediction of crop yields prior to harvest and at a low cost.

Chaurasia et al. (2011) developed empirical vegetation index VI-LAI models over five dissimilar agro-climatic regions for wheat during 2005–2006 followed by validation for the season of 2006–2007 using AWiFS optical data in four bands and in-situ measurements. NDVI as well as RVI models showed correlation ranges better (0.37–0.76 for RVI 0.65–0.84 for NDVI) than other indices. It was recommended that Leaf Area Index predictions could be used to force crop simulation model up to early-vegetative stage depending on Normalized Difference Vegetation Index and utmost vegetative to reproductive stages based on Ratio Vegetation Index.

Gontia and Tiwari (2011) used RS and GIS techniques for yield and water productivity estimation of wheat. Zand and Matinfar (2012) reported significant correlation of NDVI with Leaf Area Index and there was an excellent relationship between NDVI and yield. Kaur et al. (2016) reported that spectral indices such as NDVI, DVI, RVI, GI, and GNDVI had significant relation with grain yield. The stepwise regression analysis revealed a strong linear and positive one-to-one relationship of grain yield with spectral vegetation indices. NDVI was found to be the best index to explain the yield variability.

Various remote sensing indices are used to generate the models useful in estimating the bio-physical parameters and yield of wheat under different abiotic stress conditions. Remote sensing is a precious tool for predicting crop yield prior to harvest and at a very low-cost. Different types of spectral indices, i.e., NDVI, DVI, RVI, GI, and GNDVI have been used successfully due to their significant relationships with crop bio-physical parameters and yield.

2.7 Conclusion

Significant climatic variations experienced in the recent decades are likely to put a heavy toll on crop productivity and input use efficiency. As agriculture is directly affected by environmental factors due to specific climatic requirements of different plant species for growth and development, the changing climatic patterns will have significant effect on crop productivity in future with severe implications on input use efficiency, threatening the sustainability of agriculture and natural resources. Significant reductions in heat, radiation, nutrient, and water use efficiency in view of climate change are posing a great threat to sustainability of natural resources. Various measures aiming at enhancing heat, water, radiation, and nutrient use efficiency in different crops need to be explored including short-term field-level adjustments as well as long-term decisions. Various field level management options such as selecting appropriate sowing time, planting methods, mulch application, irrigation, and fertilizer management, etc., need to be adopted to maximize input use efficiency in agriculture without compromising crop yields. Remote sensing and GIS techniques also need to be adopted along with conventional practices to improve the accuracy of crop yield predictions in view of climatic variations and ensure their timely availability to avert any food shortages. Research on genetic improvements to develop stress-tolerant cultivars needs to be strengthened with advanced techniques. In addition to this, timely dissemination of site-specific- and accurate weather predictions needs to be ensured. Thus, in view of the predicted climatic scenarios, there is a dire need to adopt various mitigation and adaptation strategies in agriculture to sustain crop productivity and input use efficiency for achieving the sustainable development goals along with improving environmental health and food security in future.

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Balanced and Secure Micronutrients in Crop Field Influence the Efficient Utilization of Macronutrients or Vice-Versa

3

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Abstract

In agriculture, the exceptional significance of micronutrient is unavoidable, as plant relies primarily on micronutrient. Although required in small amounts of micronutrients, viz., B, Cu, Fe, Mn, Zn, they have a prominent role to play in improving yield potentials under stressed conditions. There is a large number of elements in nature out of which 16 are important for the proper growth and development of crop plants. Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorus, Potash, Calcium, Magnesium, and Sulfur are called macro- or major nutrients and required in comparatively large amounts. Iron, Copper, Zinc, Boron,

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Molybdenum, Manganese, and Chloride are the micro- or minor nutrients required in smaller quantities for the vegetative and reproductive growth of crop plants. C, H, and O contribute 85–90% of the total plant content. N gives dark green color to crop plants and it increases the vegetative growth of crop plants. It is most important for the preparation of starch in leaves and the production of amino acids. P is the constituent of certain nucleic acids, phosphatides, chromosomes, and co-enzymes. P works as a catalyst in about 60 enzymatic systems of the plants and regulates the water in plants and reduces the negative effects of salts in the plants. Ca is the important constituent of the plant cell wall and it promotes early root growth and development. In consideration of the important role micronutrients have in promoting and maintaining human health, more research is needed to determine the advantages of using the optimum level of micronutrients instead of their critical level as an indicator with regard to yield, quality, and enrichment objectives for the future.

Keywords

Macronutrients · Micronutrients · Yield · Quality · Crops · Fertilizers use efficiency

3.1 Introduction

The intensive use of mineral nutrients by crops has caused rapid depletion of micronutrient reserves from the soil causing deficiencies of micronutrients (Cakmak 2010). Since mineral malnutrition is considered to be the most thoughtful global challenge recently to humankind, among them Fe, Zn, I, or Se are the most important, causing about 60, 30, 30, and 15% of people across the globe to have deficiencies of these elements, respectively. In addition, Ca, Mg, and Cu deficiencies are common in many developed and developing countries (White and Broadley 2009). The uptake of soil minerals generally achieves via many processes to minimize deficiencies of micronutrients (Amtmann and Armengaud 2009; Gojon et al. 2009; Hänsch and Mendel 2009; Tejada-Jiménez et al. 2009). The plants are the basis of nearly all food chains, therefore, the production of biofortified seeds, fruits, or edible vegetative organs with amplified micronutrient concentrations could reduce the “hidden hunger” (Etienne et al. 2018).

To increase quality crop productivity with amplified micronutrients bio-fortified foods, nutrients management may be achieved by the involvement of organic sources, bio-fertilizers, and micronutrients (Singh et al. 2002). Micronutrient deficiency can greatly disturb plant yield, quality, and the health of domestic animals and humans (Welch 2003). Plants may also increase soil mineral availability and improve their nutrient uptake through interactions with rhizospheric microorganisms (Philippot et al. 2013). Every micronutrient has a role to play in plants so as to have potentials yields, so their role cannot be ignored.

Hence, a better understanding of the mechanisms involved in plant nutrient acquisition and distribution in edible products with increased micronutrient concentrations could pave the way to the development of improved plant varieties, and participate in the amelioration of human malnutrition (Etienne et al. 2018). An earlier study reported by Fan et al. (2008) revealed that breeding wheat for a better yield could be achieved via enhanced photosynthesis through an ample supply of both macro-(N, P, K) and micronutrients. They also observed that seed micronutrient concentrations in wheat grains remained stable due to the significant response of wheat cultivars, but decreased significantly after that time; when semi-dwarf and high-yielding wheat cultivars were used, the soil concentrations of micronutrients including Zn, Fe, Cu, and Mg either increased or remained stable (Fan et al. 2008). Ghaffari et al. (2011) found that micronutrient deficiency has emerged in most of the farmer's fields in EGP of South Asia (including India, Pakistan and Bangladesh), due to continuous use of NPK fertilizers, which leads to shrinkage of the vital micronutrients in intensively cultivated areas. Similarly, Jamal and Chaudhary (2007) reported that about 50% of applied N and 70% of applied K in the soil of rice–wheat systems of South Asia remain unavailable to a crop due to leaching, fixation, and volatilization. Malakouti (2008b) found that macronutrient use efficiency was improved up to 50%, when applied with micronutrients, either through soil application, foliar spray, or seed treatment. Rasheed et al. (2004) and Vilela et al. (1995) also reported that integrated use of macro- and micronutrients increased a significant improvement of maize grain yield as well as nutrient use efficiency. Witt et al. (2006) clearly indicated that crop-specific site-specific integrated nutrient management is essential for the sustainability of crop production under changing climate. In the review, an attempt was made to overview the earlier findings related to combine the application of micronutrients for the efficient utilization of macronutrients or vice versa.

3.2 Essential Macro- and Micronutrients for Sustainable Crop Production

A combination of macronutrient and micronutrient gives the soil its optimum health. The essential macronutrients needed by the soil are Nitrogen (N), Phosphorous (P), Potassium (K), Sulfur (S), Calcium (Ca), and Magnesium (Mg) (Table 3.1). The essential micronutrients are Chlorine (Cl), Iron (Fe), Boron (B), Manganese (Mn), Zinc (Zn), Copper (Cu), and Molybdenum (Mo). Further, it is very important to know the critical limit of each micronutrients in the soil below which it shows the deficiency symptoms.

The deficit of macronutrients leads to poor plant growth and potential for disease; while reduced flowering and yellow-green coloration are due to the deficiency of micronutrients. Therefore, it is important to have a balance of macro- and micronutrients in crop fields for desirable yield. Having them in the right quantities makes the growth of the crop plants healthy and strong. The macronutrients help

Table 3.1 Deficiency symptoms of micronutrients with the critical limits in the soil

Nutrients	Critical limits (mg kg^{-1})	Deficiency symptoms of specific nutrients	Major functions	References
Zn	0.6	Generally interveinal of leaves yellowing. Some plant species dicotyledons often have shortened internodes, as a result, leaves are clustered on the stem	• Constitute of several enzyme systems • Helps regulate metabolic reactions in plants • Helps in the utilization of N and P in plants • Helps in reproduction and formation of growth hormones and protein	Weir and Cresswell (1993), Weir et al. (1995), Alloway (2008)
B	0.5	Boron is associated with cell growth. Therefore, symptoms of B deficiency are showed at growing tips of the shoot or root, through generally stunting and distortion of the growing tip and yellowing of lower leaf tips	• Essential for proper pollination • Helps in seed and cell wall formation • Is an enabler for the mobility of energy in the plants • Helps in calcium and protein synthesis	Camacho-Cristóbal et al. (2008), Koshiba et al. (2009), Wani et al. (2013)
Fe	4.5	Fe symptoms generally show in interveinal chlorosis of younger leaves, since main veins remain green. However, in severe cases, the whole leaf may become lightened	• Involved in the biosynthesis of chlorophyll • Plays an essential role in enzymes and RNA metabolism • Responsible for oxidation-reduction in plants and regulates respiration and photosynthesis	Wani et al. (2013), López-Millán et al. (2013), Eroglu et al. (2016)
Mg	2.0	Mg deficiency causes interveinal chlorosis of leaves with necrotic spots and stunted root growth and development	• Activates and regulates enzymes • Translocates Fe • Responsible for nitrogen metabolism and chlorophyll synthesis	Wani et al. (2013), Hermans et al. (2013), Guo et al. (2016)
Mo	0.1	Due to Mo deficiency, the leaf turns to light green. Except on the leaf veins overleaf showing dead necrotic spots. Mo shortage limits the development	• Helps in nitrogen fixation in legumes • Involved in nitrogen metabolism of plants	Mengel and Kirkby (2001), Hamlin (2007), Wani et al. (2013)

(continued)

Table 3.1 (continued)

Nutrients	Critical limits (mg kg^{-1})	Deficiency symptoms of specific nutrients	Major functions	References
		of flower and also underdeveloped the growth of the plant		
Cu	0.2	Deficient Cu causes the interveinal chlorosis of leaves; while in extreme cases leaves are rosetting and permanent wilting. Cu insufficiency causes pollen sterility, yellowing and curling of leaves and reduces the number of ears in cereals	• Helps the formation of vitamin A in plants • Enables formation of ethylene in ripening fruit • Aids in carbohydrate and nitrogen metabolism	Yruela (2005), McCauley et al. (2009), Wani et al. (2013)
Ni	0.1	Ni deficiency can lead to the accumulation of toxic urea in plant tissues. Ni insufficiency limits the germination, and seedling growth; dwarfing internodes and collapse the formation of flowering and reduced the kernel filling	• Required by seeds to germinate and grow • Responsible for the absorption of iron	Rahman et al. (2005), Sengar et al. (2008), Wani et al. (2013)
Cl	8.0	Cl insufficiency causes chlorosis and burning of leaf tips, leading to bronzing and drying; over-wilting and leaf fall reduce the yield	• Plays an important role in opening and closing of stomata (which is important for photosynthesis) • Increases the water-holding capacity of plant tissue	Wani et al. (2013), Heckman (2016)

create new plant cells that organize into the plant tissue. Without these nutrients, growth and survival will not occur.

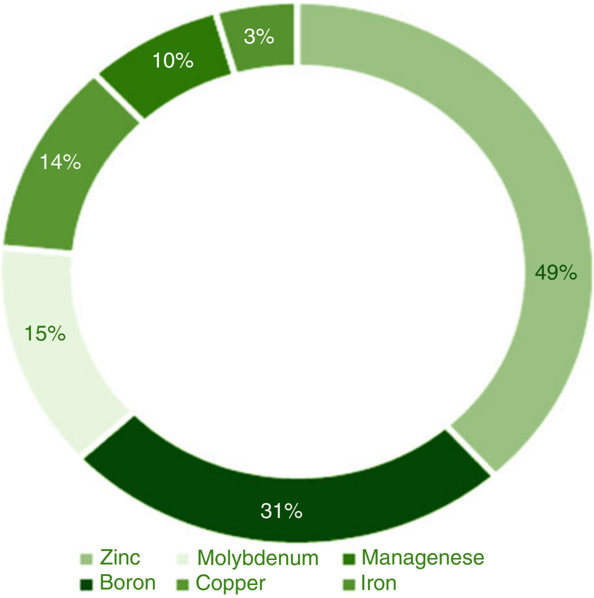
3.2.1 How Macronutrients Help Plants for Proper Growth and Development

Macronutrients help plants grow lush and green in several ways. For example, N—helps foliage grow strong and affects the plant's leaf development. It also gives plants their green color due to its assistance with chlorophyll production; P—assists with the growth of roots and flowers. It also helps plants survive harsh climates and environmental stressors; K—strengthens plants, helps contribute to early growth, and assists the plants in retaining water. It also keeps the plants from contracting diseases and insects; Mg—contributes to the green coloration of the plants; S—resists disease and helps form and grow seeds. It also aids in the production of amino acids, proteins, enzymes, and vitamins, and Ca—aids in the growth and development of cell walls. Well-developed cell walls help to resist disease. It is also helpful in cell metabolism and the uptake of nitrate.

3.2.2 How Micronutrients Provide Major Benefits to the Soil

Micronutrients help plants for proper growth and development in several ways. For example, Fe—required for the formation of chlorophyll in plants; Mn—assists iron in chlorophyll formation. It also serves as an activator for enzymes in the growth process; Zn—an important plant regulator, it is essential in root and plant growth; B—regulates the metabolism of carbohydrates in plants. It is critical for new growth and assists in pollination, fertilization, and more; Cu—activates enzymes in plants; Cl— required for photosynthesis and root growth; Mo—needed by plants for utilization of nitrogen. Without Mo, plants cannot transform nitrate nitrogen into amino acids and Ni—required to complete the life cycle of the plant and viable seed. However, nowadays universally, deficiency of different micronutrients prevails which needs to be addressed (Fig. 3.1).

Fig. 3.1 Global micronutrient deficiency status (Source: Graham 2008)



3.3 Importance of Macro- and Micronutrients for Sustainable Crop Production

Micronutrient deficiency is widespread in plants, animals, and humans, especially in many Asian countries, due to the calcareous nature of soils, high pH, low organic matter, salt stress, continual drought, high bicarbonate content in irrigation water, and imbalanced application of fertilizers. For example, if irrigation water with an HCO_3^- concentration of 4 mEq l^{-1} (244 mg l^{-1}) is added to a field crop or an orchard at the rate of 5000 m^3 ha^{-1} $year^{-1}$, the amount of added HCO_3^- to the soil would exceed 1 ton ha^{-1} $year^{-1}$ (about 1220 kg ha^{-1}). The following equations show why high pH and high bicarbonate levels reduce the availability of micronutrients in the calcareous soil:

$$\mathrm{CaCO_3 + H_2O \Leftrightarrow Ca(OH)_2 + CO_2}$$

$$\mathrm{CaCO_3 + H2O \Leftrightarrow HCO^-{}_3 + Ca^{++} + OH^-}$$

$$\mathrm{CaCO_3 + H_2O + CO_2 \Leftrightarrow 2HCO^-{}_3 + Ca^{++}}$$

$$\mathrm{CaCO_3 + 2H+ \Leftrightarrow 2HCO^-{}_3}$$

$$\mathrm{HCO - {}_3 \Leftrightarrow CO \uparrow {}_2 + OH - {}_2OH - +M + + \Leftrightarrow M\ (OH)_2 \downarrow}$$

where M^{++} is a micronutrient. As a result of producing more HCO_3^- and OH- in the rhizosphere, the pH of the soil solution and, consequently, the pH of plant sap can increase to a level that causes micronutrients to precipitate, lowering the level of their availability as a whole. Ali-Ehyaee (2001) studied the status of micronutrients in the soils of four provinces in Iran and reported that there is a negative relationship between the percentage of soil organic matter and micronutrient deficiency. Sillanpaa's (1990) broad study conducted in several countries revealed that crop yield, or soil and plant analytical data, or a combination of both indicated some degree of micronutrient deficiency, especially Zn, at all Iraqi and Pakistani study sites. In the most acute case of Zn deficiency, rice yield was more than tripled by the application of 12 kg of Zn ha^{-1}. Zn deficiency was more frequent than that of any of the other six micronutrients included in the study. Some degree of Zn deficiency was estimated to exist at almost 50% of the sites investigated. The occurrence of Zn deficiency was highest in Iraq and Pakistan (at almost every study site), followed by Nepal, Turkey, and Thailand, whereas it occurred with the lowest frequency in Tanzania, Finland, Zaire, and Zambia. These findings are in good agreement with analytical data subsequently collected from the same countries, especially those for calcareous soil in Iran (Malakouti and Tehrani 2005). The reported frequencies of Zn deficiency might have partly been due to the fact that crops susceptible to Zn deficiency, such as rice and maize, were important crops for many of the countries in which the studies were conducted, and consequently, they were often selected as test crops. The response of crops to Zn varied widely, and in an extreme case, no grain yield was obtained without the application of Zn. In addition, there were a

Table 3.2 The percentage of nutrient-deficient soils among the 190 soils tested in 15 countries (data source: Sillanpaa 1990)

	N	P	K	Fe	Mn	Zn	Cu	B	Mo
Type of deficiency	% nutrient								
Severe	71	55	39	0	1	25	4	10	3
Buried[a]	14	18	19	3	9	24	10	21	12
Total	85	73	55	3	10	49	14	31	15

[a] Soil low in a nutrient, but nonresponsive due to some other limiting factors or to non-susceptibility of the test crop

Table 3.3 Micronutrients and their sensitive crops (Source: Katyal 2018; Ganeshamurthy et al. 2018)

Micronutrients	Sensitive crops
Zn	Corn, onion, soybean, beans, paddy, peach, grapes
Fe	Sorghum, tree crops, blueberries, roses, grapes, nut trees
Mg	Peas, oats, apples, sugar beet, beetroot, citrus
Cu	Wheat, corn, onion, citrus, lettuce, carrot
B	Alfalfa, cauliflower, celery, grapes, apples, peanut, beets, rapeseed
Mo	Alfalfa, crucifers (broccoli, cabbage), citrus, most legumes activity

number of sites in which the application of Zn did not affect the yield quantitatively, but Zn content in the soil and plants was low enough to indicate problems for animal nutrition. Although some high levels of Zn in soils and plants were measured, no clear evidence of Zn toxicity to crops was found. The percentage of nutrient-deficient soils among the 190 soils tested in 15 countries is shown in Table 3.2 (Sillanpaa 1990).

Further, some crops are more sensitive to the deficiency of certain specific macronutrients and hence grain yields thus adversely affected. Therefore, it is very important to know the crop-wise sensitivity of different micronutrients to address the issue well in time for having potential and quality produce (Table 3.3).

Micronutrients have their different roles to play (Fig. 3.2) to mitigate the adverse effects of the stresses whether it is water or salt stress. Therefore, the crop will not be adversely affected under different stresses if the soil has sufficient/adequate micronutrient inherent capacity.

3.3.1 Improving Crop Yield and Quality with the Combination of Macro- and Micronutrients

Plant, animal, and human micronutrient requirements are rather low, which is why they are called micro-elements; however, they are essential for vital cell functions. Micronutrient deficiency can greatly disturb plant yield and quality, and the health of domestic animals and humans (Cakmak 2002; Malakouti 2007). Extensive research on the effects of micronutrient fertilizers on crop yield and quality has been

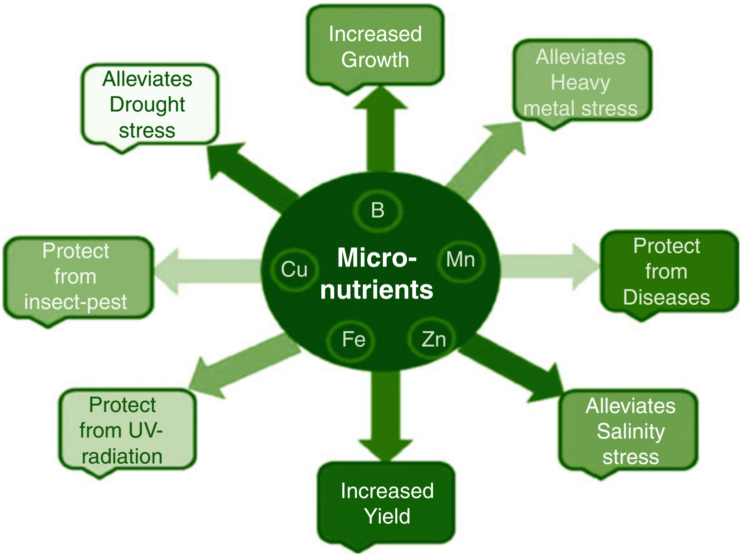


Fig. 3.2 The responses of micronutrients in biotic and abiotic stresses (Source: Tripathi et al. 2015)

Table 3.4 Average canola yield (kg ha^{-1}) in response to the combination of macro- and micronutrient fertilizers. (Data source: Malakouti and Tehrani 2005)

	Treatments		Yield increase	Treatment		Yield increase
Locations	NPK	NPK + Fe	(%)	NPK	NPK + Zn	(%)
1	2051	2578	26	3221	3513	9
2	1043	1437	38	2467	3169	28
3	2403	3221	34	1409	1579	12
4	3036	3694	22	2243	3816	70
5	2831	3334	18	2051	2578	25
Mean	2273	2853	28	2278	2931	29

conducted during the past decade (Malakouti et al. 2005). Results of a broad-based study conducted in 815 irrigated wheat-growing regions of Iran between 1995 and 1996 in order to evaluate the effect of micronutrients on increasing wheat grain yield are presented in Table 3.4. The addition of each micronutrient (Fe, Zn, Cu, and B) or a combination of Fe + Zn + Cu + B to NPK fertilizer increased grain yield. The highest yield was obtained by adding all the micronutrients to NPK fertilizer (Malakouti 2000).

Malakouti (2007) revealed that if only one micronutrient were to be added to calcareous soils, Zn is obviously the best choice for yield improvement. Another experiment carried out in the Karaj region of Iran to test the ability of micronutrients to improve the yield of wheat grain also showed that grain yield increased from 3910 kg ha^{-1} to as much as 4926 kg ha^{-1}, a 26% increase (Malakouti 2000). As reported by Malakouti and Tehrani (2005), researchers from the Iranian Soil and

Water Research Institute conducted two experiments. In the first experiment conducted with canola plants, they found that the addition of micronutrients increased yield (Table 3.4). In the second experiment conducted with potato and sugar beet in five Iranian provinces, they concluded that balanced fertilization of potato and sugar beet gave good results in terms of the average yield of 20 fields in each of the five provinces (Table 3.5).

3.3.2 Improving Crop Yield and Quality Through the Application of Balanced Fertilizers

It was commonly believed that the thousand-kernel weight index was genetically determined, and that nutrient management would not affect this parameter in wheat. This notion was tested in a greenhouse and fields (Malakouti et al. 2005). The results revealed that the thousand-kernel weight index increased from 44.0 g to 48.4 g pot^{-1} (10% increase) due to balanced fertilization, and that grain yield increased from 7.1 g to 8.3 g pot^{-1}, an increase of 17%, which is significant at the 1% level, in a greenhouse experiment (Malakouti 2008a). He also found that the mean yield increase from 4353 kg ha^{-1} to 4640 kg ha^{-1}, as well as an increase in mean thousand-kernel weight from 38.49 g to 38.94 g due to balanced fertilization (Figs. 3.3 and 3.4).

Malakouti (2008a) also found that in Kohgilouyeh and Boyerahmad provinces of Iran, wheat, rice, and grape yields increased from 3220, 4697, and 10,540 kg ha^{-1} to 4117, 7508, and 19,040 kg ha^{-1} (28%, 60%, and 81%), respectively, whereas under normal conditions, mean yield increase in wheat-rice, corn, potato-onion, and oilseeds were 15%, 30%, 25%, and 20%, respectively. In other words, the application of micronutrient fertilizers to micronutrient-deficient soils is associated with improved yield and crop quality for cereals, corn, beans, forages, and oilseeds (Malakouti and Tehrani 2005; Malakouti 2007).

3.3.3 Improving Fertilizer Use Efficiency with Micronutrient fertilizers

Based on the increases in both grain yield and mineral fertilizer use efficiency, it can be suggested that the use of micronutrient-enriched fertilizers results in significant economic benefit to farmers. Fertilizer use efficiency (FUE) for different crops can be increased by the application of micronutrients. It is recommended that to maximize FUE in crop production, micronutrient fertilizers should be applied based on soil-testing values in all calcareous soils. For example, according to the data in (Malakouti and Tehrani 2005; Table 3.2), on potato farms, the average yield increases due to micronutrient fertilizer application was 13% (the average yield of potato in different provinces increased from 27,360 to 30,960 kg ha^{-1}). Then, FUE, by assuming an application rate of 50 kg of micronutrient fertilizer ha^{-1}, will be (30,960-27,360): 50 = 72 kg potato kg^{-1} of micronutrient ha^{-1}(kg ha^{-1}). Therefore,

Table 3.5 The average yield (kg ha^{-1}) of potato and sugar beet is influenced by the addition of micronutrients (Data source: Malakouti and Tehrani 2005)

Locations of the potato field	Treatments		Yield increase (%)	Locations of sugar beet field	Treatment		Yield increase (%)
	NPK	NPK + Micronutrients			NPK	NPK + Micronutrients	
Semnan	29,000	32,000	10	Fars	6497	6561	1
Hamadan	41,500	46,500	12	Khorasan	4230	4545	7
Kerman	13,900	17,500	26	Arak	9853	10,635	8
Karaj	16,500	22,100	31	Keraj	6450	7500	16
Ardabil	35,500	36,700	3	–	–	–	–
Mean	27,360	30,960	16	Mean	6759	7310	8

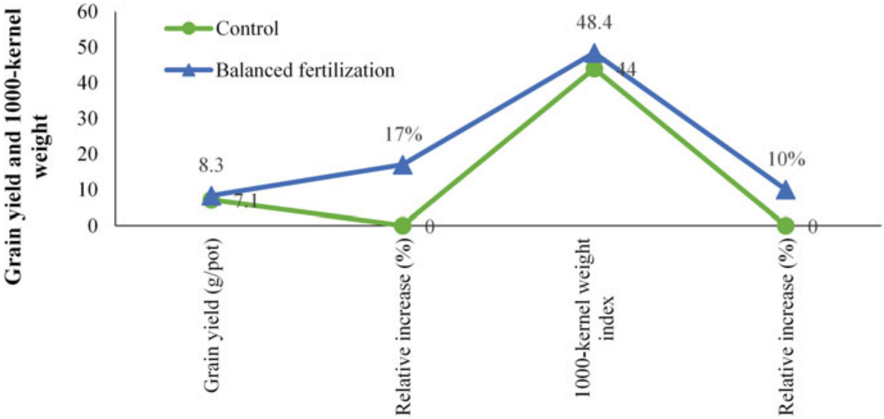


Fig. 3.3 Effect of balanced fertilization on grain yield and 1000-kernel weight index of different wheat cultivars (Adapted from Malakouti 2008b)

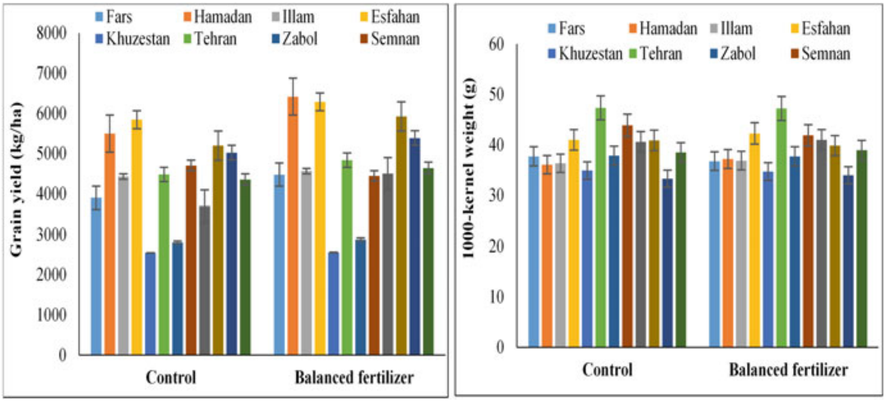


Fig. 3.4 The effect of balanced fertilization on grain yield (kg/ha) and thousand-kernel weight index (average of 140 fields during a two-year experiment in various provinces) (Adapted from Malakouti 2008a)

it seems more logical to practice balanced fertilization in crop production. The data from the experiments revealed that, as a whole, balanced fertilization (NPK + micronutrients), in contrast to the control (NPK), was the best (Malakouti 2000; Malakouti and Tehrani 2005).

Micronutrient deficiency limits plant growth and affects crop yield, especially in calcareous soil. The results revealed that the application of balanced fertilization significantly increased grain yield. Field tests of more than 2500 different experiments have shown that micronutrients have a significantly positive effect on crop yield and quality. Our studies have shown that micronutrients also ensure the efficient use of macronutrients. Cakmak (2002), Malakouti (2007), Cakmak (2008), and Malakouti et al. (2008) also reported the same results.

3.4 Conclusion

There is an urgent need to improve the micronutrient status of soils in contrast with macronutrient. Despite the large body of data that clearly indicates that crop productivity improves with the application of micronutrients with macronutrients. This implies that there is a large gap between research and education and extension in transferring valuable scientific information to farmers and in changing their habitual use of conventional fertilization. Despite the progress already made, more effort is still needed to increase Zn fertilizer efficiency, the awareness of environmental-related issues, and the economic aspects of micronutrients, so as to achieve sustainable agriculture for food security and human health.

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Use of Agrochemicals in Agriculture: Alarming Issues and Solutions

4

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Abstract

Agricultural growth affects the economic growth of a country through the supply of food and other raw materials to nonagricultural sectors, and it is quite obvious that agricultural productivity through judicious use of inputs could play a vital role in structural change in the economy. But the indiscriminate use, rather misuse of chemical inputs in agriculture, has led to many problems in our ecosystem. A rough estimate of pesticide usage among the different developing countries shows that East Asia (including China) and Latin America consume almost 70% of the

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total pesticide use with only 4% in Sub-Saharan Africa. Due to the irrational use of agrochemicals, the degree of pollution in soil, air, water, and ecosystem as a whole is a big concern for us. A typical estimate of soil surface nitrogen balance for agricultural land in India reveals that inorganic fertilizer is the major contributor of nitrogen inputs in the ecosystem (10.8 Tg N) followed by manure (1.53 Tg) and a positive balance of 2.32–1.89 Tg N was found which is responsible for various environmental hazards. The judicious use of inputs matching with the requirement of the crops and their application below residue detection limits are the priority areas to protect our future generations from hazardous effects and to provide food to every mouth on the other hand. We have to assess the harmful effects of various chemical inputs used in agriculture continuously, and suitable strategies are to be developed orienting towards the rational use of inputs. The major impacts of chemicals and their contaminants are alterations in species diversity, degradation of physical–chemical–biological parameters of soil, water, and atmosphere, making them of inferior quality. This chapter describes the impact of alarming uses of chemicals on agricultural systems, water bodies as well as on the environment on one hand, and framing of suitable strategies targeting judicious use of inputs in agriculture on the other. Strategies include sustainable resource management through conservation agriculture practices, site-specific nutrient management, precision farming, integrated management of pests and diseases, agricultural waste management, and use of nano-molecules in addition to some biotechnological tools and policy interventions.

Keywords

Agrochemical inputs · Food · Environment

Abbreviations

BOD	Biological oxygen demand
CA	Conservation agriculture
CCC	Critical coagulation concentration
CT	Conventional tillage
FAO	Food and Agriculture Organization
GMO	Genetically modified organism
GPS	Global positioning system
HCH	Hexachlorocyclohexane
HYVs	High yielding varieties
IGP	Indo-Gangetic Plains
KCC	Kisan credit card
NUE	Nutrient use efficiency
ORP	Operational research project
PA	Precision agriculture
PPVFRA	Protection of Plant Variety and Farmers Right Act

QUEFTS	Quantitative evaluation of the fertility of tropical soils
RTKGPS	Real-time kinematic GPS
SOC	Soil organic carbon
SSNM	Site-specific nutrient management
UV	Ultraviolet
VRI	Variable rate irrigation
VRNA	Variable rate nutrient application
VRPA	Variable rate pesticide application

4.1 Introduction

Chemical fertilizers as well as pesticides are indispensable in crop production. For producing an appreciable quantity of food for our ever-increasing population, it is quite impossible to stop the use of agrochemicals in agriculture. However, the indiscriminate use, rather the misuse of this sort of chemical inputs, has led to many problems in our ecosystem. Due to improper use, these chemicals reach the environment as pollutants after leaving the soil-plant system. The degree of pollution in soil, air, water, and ecosystem as a whole is a big concern for us. The residues of agricultural chemicals in soil, water, and air causing pollutions have been reported by many countries (Ridolfi et al. 2014; Alvarez et al. 2017). The excessive use of nitrogenous fertilizers causes depletion of the stratospheric ozone layer through the production of nitrous oxide. This is having a tremendous impact as we all know that ozone layer acts as a shield against harmful UV rays. Fertilizers applied to fields are causing pollution in water bodies by draining rainwater or irrigation water to ponds, rivers, or lakes. Water quality is being deteriorated through eutrophication. Again the seepage of chemical inputs also pollutes the groundwater. Water pollution is also occurring even at a lower concentration of pesticides; these pesticides are becoming a threat to the environment (Agarwal et al. 2010). Several pesticides applied to crops are entering into the food chain *vis-à-vis the* human system, thus causing harmful effects on human health (Dasgupta et al. 2007). In most developing counties, agricultural chemicals lead to serious pollution (Tunstall-Pedoe et al. 2004; Tirado et al. 2008). In rural China, nearly half of the groundwater resources were polluted through agricultural chemicals and the safety of drinking water is under threat now (He 2013). The green revolution in Asian countries was primarily aimed at increasing the cereal production system for food security and actually, it increased the usage of synthetic inputs. The crops respond readily to added synthetic chemical inputs. Undoubtedly, the use of these sorts of inputs increased the potential productivity of the crops. But we did not emphasize soil quality and environmental hazards.

In the present context, scientists are promoting organic inputs which are a holistic system for handling the environment, health, and sustainability (Dubey 2013), thus addressing the issue of environmental protection. Sometimes we are talking about integrated management of the soil as well as crops in which loads of chemicals are reduced through integrating the chemicals with bio or organic things with the restoration of biodiversity. GMO agriculture also initially pointed to increase the productivity of the crops with reduced use of agro-chemicals. It is although a debatable issue that whether GM crops have been proved to have reduced chemical load with increased yield sustainability.

Though agrochemical is a crucial component of the agricultural production system, the misuse of these products poses a serious problem. Agrochemicals are very important for agricultural production, but the actual problem is its misuse. The consumption of pesticides per unit area in a country like India is far below the average consumption of other developed countries, but pesticide residue is a big problem (Abhilash and Singh 2008). We have to come out with techniques through which we can produce safer molecules regardless of their doses of applications. The judicious use of inputs matching with the requirement of the crops and their application below residue detection limits are to be perceived as the focus area to protect our future generations from hazardous effects and to provide food to every mouth. Therefore, it is the need of the era to assess the harmful effects of various chemical inputs used in agriculture continuously, and suitable strategies would certainly be oriented toward the rational use of inputs. Considering the important aspects, this chapter describes the impact of alarming uses of chemicals on agricultural systems, water bodies as well as on the environment on one hand and framing of suitable strategies targeting judicious use of inputs in agriculture on the other. Strategies include sustainable resource management through conservation agriculture practices, site-specific nutrient management, precision farming, integrated management of pests and diseases, agricultural waste management, and use of nanomolecules in addition to some biotechnological tools and policy interventions.

4.2 Influence of Agricultural Inputs on Economic Development

In recent years, agricultural productivity has enhanced a lot in most of the developing countries and it is thought that this enhanced productivity might contribute to the economic development of the country. This is the question of the hour as to how agriculture plays a role in the economic growth of the country. Actually, the institutional changes in the input and service delivery system are supposed to be the crucial factors for developing agriculture, more specifically for smallholder's agriculture. In a highly populous country like India, increasing productivity through the use of higher inputs along with advanced agricultural technologies are the key options for the promotion of agricultural growth. Under the circumstances, it is very much necessary to assess the growth rate of input use with the opportunity for developing market accessibility; institutional interventions are very much required for improving the situation. In India, during the last two decades, the government has launched few schemes like PPVFRA (Protection of Plant Varieties and Farmers' Rights Act), KCC (Kisan Credit Card), etc. for improving judicious use of inputs along with better credit delivery. Still, we are searching for the answer that whether there are any significant changes in input use and delivery system that could benefit our smallholder farmers and whether the institution has a role in bringing out these sort of changes. Venkatesh and Nithyashree (2014) emphasized easing procedural norms for getting the benefits of institutional credits for small and marginal farmers. Moreover, updated information on agriculture technologies and markets and communication technologies may be infused within the present extension system to reach it to remotely located farm households. Timely availability of agriculture inputs, assured irrigation facilities, newer varieties, mechanization, financial support, timely availability of pesticides, fertilizers, etc. may help to improve the agricultural sector *vis-à-vis* the economy as a whole (Ganesan and Pushpavalli 2007).

Through improving the status of agriculture, several countries have achieved sustained economic growth. However, with its advancement, the role of agriculture has declined for employment generations, net output production as well as the country's overall economic growth. The economic growth of Africa has shifted from agriculture to other economic sectors in recent years (McMillan and Harttgen 2014). Very often, the rural smallholder farming community face many problems. The international economic environment has brought about some beneficial changes in world agriculture, but there remains a serious concern for agricultural protection policies through which the developing countries had limited access to international markets. It has long been perceived that advances in agriculture could influence the shift of labor forces from agriculture to other sectors having increased productivity with better incomes. Collier and Dercon (2014) studied the economy of the developing countries where agriculture is a priority investment sector and tried to assess why agriculture is the targeted area for investment in poor countries.

With the advent of the green revolution in Asian countries, there was a significant jump in cereal yields (roughly around 200%+). This period from the late 60s to early 70s underpinned the economic growth to boost up. Diao et al. (2010) explained why Africa has not achieved higher economic growth due to the lack of green revolution. The green revolution led to the use of new improved genetic stocks with higher use of chemical inputs (Murgai 2001; Restuccia et al. 2008; Kumar et al. 2021). These agricultural inputs, viz., improved seeds, fertilizers, plant protection chemicals, etc. are partially credited with the large increases in agricultural growth in Asia during the 1960s. It was seen that the pace of progress was sluggish in those countries which have lower incomes. It clearly suggests strong relationships between the economic growth of a country and growth in agriculture. Agriculture growth is indirectly dependent on rainfall distribution, and due to climate change incidents with a very erratic pattern of rainfall distribution throughout the globe, the growth rate in agriculture is fluctuating. The new economic policies with the changing governments sometimes had a great impact on the national economy. Very often, untimely and inadequate finance or policies taken up by the governments had a negative impact on farmers (Dwivedy 2011). In many developing countries, agricultural production has been directly supported by subsidies to various inputs and in most cases, it brings benefits to larger farmers rather than the smallholding farmers (De Gorter and Swinnen 2002). Thus, it is quite obvious that agricultural productivity through judicious use of inputs could play a vital role in structural change in the economy.

4.3 Use of Chemical Inputs in Agriculture: An Overview

The chemical inputs are indispensable for crop production with relatively less effort (Alix and Capri 2018). The advent of high yielding varieties (HYVs) of cereals in India during the mid-1960s resulted in a paradigm shift in agriculture; low input–low output subsistence farming has been changed into input-intensive, high-output commercial farming. The low-yielding indigenous varieties were replaced with HYVs which were not only more responsive to nitrogenous fertilizers but at the same time became more susceptible to pests and diseases. Consequently, usage of chemical inputs like fertilizers and pesticides was increased several folds leading to the increased growth rate of food grain production from 2.4% to 3.5% per annum before and after 1965, respectively (Eliazer Nelson et al. 2019). Since then, the usage of chemicals in agriculture gradually increased till 2010–2011 and thereafter stabilized. Some facts and figures regarding the usage of chemical inputs in Indian agriculture and the level of output can be viewed in Table 4.1.

An extensive study by FAO in different developing countries revealed that excluding China, all other developing countries, as a whole, use about 60% of fertilizers on cereals, rice being the major consumer with 33% of the total use. The study also suggests that allocation of fertilizers to cereals is roughly equivalent to the proportion of the harvested area of those cereals (55%) in the developing countries with the exceptions of sorghum and millets, coarse-grained cereals, which consume a lesser amount of fertilizers. Nonedible crops, fruits, and vegetables have a relatively larger share in total fertilizers usage relative to their harvested area. Among the industrial crops, sugarcane and cotton account for a relatively larger share of total

Table 4.1 Chemical inputs (fertilizers and pesticides) and output (foodgrain production) scenario of India

Chemical inputs				[b]Output (in terms of total food grain production) in million tons			
Fertilizers consumption[a] (total N + P_2O_5 + K_2O) in '000 tons							
1950–1951	1980–81	2010–2011	2018–2019	1950–2051	1980–2081	2010–2011	2018–19
69.8	5515.6	28,122.2	27,228.2	50.82	129.59	244.5	285.0
Pesticide consumption[b]							
Pesticides (technical grade) in'000 tons	2000–2001	2010–2011	2018–2019				
	43.58	55.54	53.45				

[a]Data Source: Statistical Database (2020), Fertilizer Association of India: https://www.faidelhi.org/general/con-npk.pdf

[b]Pocket Book of Agricultural Statistics (2019), Ministry of Agriculture and Farmers Welfare, Govt. of India, p. 26, 45

fertilizer usage in relation to their harvested area (9 and 4%, respectively) while the corresponding figures for crops like pulses, root, and tuber crops are smaller. It was also predicted that per hectare usage of fertilizers in North Africa and a fraction of Asia will exceed the average fertilizer usage of the developed countries after 2010, whereas the same will be continued to become very low in the case of Sub-Saharan Africa and probably will not support the sustainability of its agriculture (Alexandratos 1995).

Similarly, like fertilizers, rapid growth in the usage of pesticides in developing countries occurred during the late 1960s and 1970s due to the spread of areas under HYVs as discussed earlier. In the mid of 1980s, about one-fifth of globally produced pesticides was consumed by the developing countries (530,000 tons in terms of active ingredients during 1985) with a relatively higher share for insecticides (50%) and comparatively lower for fungicides (20%) and herbicides (10%). A rough estimate of pesticide usage among the different developing countries shows figures like this: East Asia (including China) 38%, Latin America 30%, North Africa 15%, South Asia 13%, and Sub-Saharan Africa only 4%. Consumption of pesticides in these countries increased to an extent of 1% during the second half of the 1980s. But, since the 1990s, a declining trend has been observed in the worldwide usage of pesticides in developing countries as a whole (Alexandratos 1995).

In the last decade starting from 2010, developed countries like North America, Europe, and South America have not witnessed much increase in the usage of synthetic nitrogenous fertilizers in terms of nutrients (approximately 12 million tons to 16 million tons of nitrogen for North America and Europe and almost consistent at seven million tons for South America). Similar trends can be observed in these countries for phosphate and potash fertilizers with a rough value of 4–5 million tons of nutrients for each fertilizer. On the other hand, in the case of total pesticide usage (in terms of the active ingredient), the value is comparatively on the lower side (roughly 0.5 lakh tons) in different developed countries like Australia, Canada, Germany, and Denmark, but for the United States of America, the value hovers around 4.5 lakh tons during the period between 2000 and 2014 (Tsion and Steven 2019).

Usage of chemical inputs in the agriculture sector of the United States of America is worth to be mentioned here as the country is playing a vital role in regulating the chemical usage scenario of the developed countries as a whole. Like other developed countries, fertilizer usage in the United States (US) peaked its pace from 7.46 million short tons (1 short ton approximately is equal to 907 kg) in 1960 to 23.68 million short tons in 1981 and after 1982 stabilized with minor fluctuations. On the contrary, total pesticide use in the USA in the five dominant crops (corn, soybean, fall potato, cotton, and wheat) hovered around 400–500 million pounds (1 pound is equal to 0.453 kg) during the period 1980 to 1990, surged after 2005 and reached to 634 million pounds in 2014. It has also been observed that among the total pesticide, the share of herbicide has been increasing gradually in the USA during this time (Hellerstein et al. 2019) and leveled-off in the last decade.

There is a nexus between the usage of chemical inputs (fertilizers, pesticides) and agricultural production. It will move in a positive direction until the usage of

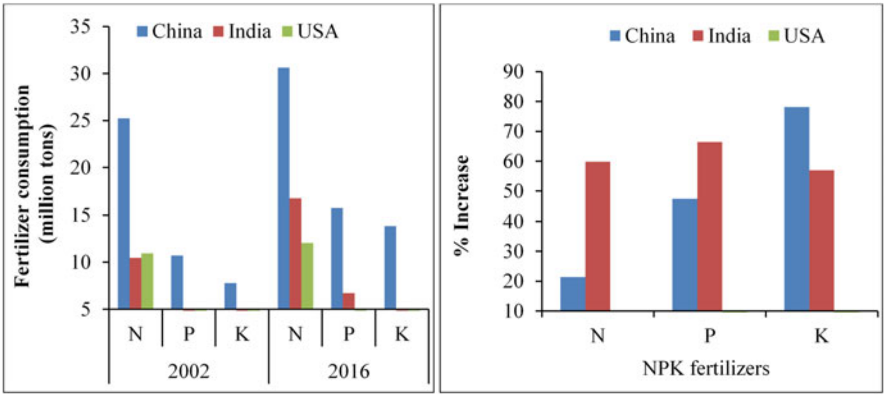

Fig. 4.1 Fertilizer consumption and % increase in NPK fertilizer (2002–2016) in different countries (Data Source: Srivastava 2020)

chemicals inputs is balanced, but overuse may lead to multifaceted damage to the environmental system (Srivastava 2020; Mandal et al. 2020). Though the usage of agrochemicals in various developing and developed countries in the world has not been changed to a great extent in the last decade (after 2010), a substantial plunge can be noticed before and after 2010 in different parts of the world. It is also worth mentioning that the usage of agrochemicals has increased several folds in developing countries over developed countries. A comprehensive fact has been presented (Fig. 4.1) depicting the comparative usage as well as % increase in chemical fertilizers in China, India, and the USA during 2002 and 2016.

It is clear from these discussions that in the last decade, countries in the world have not increased its own usage of chemical fertilizers and pesticides but the usage in the developing countries is gradually increasing in relation to the developed countries.

4.4 Indiscriminate Use of Fertilizers and Pesticides and Its Impacts

4.4.1 Fertilizers and Its Impacts

4.4.1.1 Impact on Agricultural Ecosystem

Fertilizers are the agrochemicals carrying nutrients elements for promoting the growth of plants (N, P, K, S, etc.) Indiscriminate uses of these fertilizers leave unutilized particles of fertilizer nutrients into the environment. These nutrient elements may get deposited into the ecosystem as solid particles suspended in rainwater (wet deposition) or may be transported as individual dry particles (dry deposition). Thus, nitrogen can be deposited as NO_3^- or NH_4^+, phosphorous as PO_4^{3-}, sulfur as SO_4^{2-}, etc. on terrestrial ecosystems. The deposition of nutrients from fertilizers may undergo several transformations like nitrification, denitrification, volatilization, etc., and biogeochemical processes like percolation, leaching, seepage, etc. leading to an imbalance in the ecosystem and environmental hazards.

Singh and Tripathi (2000) reported that nitrogen deposition rates range between 2.5–20 kg N ha^{-1} $year^{-1}$ and may reach up to 30–64 kg N ha^{-1} $year^{-1}$ (5–25 kg N ha^{-1} $year^{-1}$ in the eastern USA, 5–60 kg N ha^{-1} $year^{-1}$ in northern Europe during the year 2000), leading to an imbalance in mineral nutrition. They projected a 60% increase in combined annual nitrogen release in the terrestrial ecosystem by the year 2020 due to an increase in fossil fuel burning and fertilizer use, of which two-third will occur in Asia.

Despite this huge nitrogen input, availability of nitrogen is often low in the agroecosystem owing to its several kinds of losses, particularly in the tropical agroecosystem, like ammonia volatilization from animal waste, soil, and vegetation, denitrification as well as gaseous emissions of nitrous and nitric oxide. A typical estimate of soil surface nitrogen balance for agricultural land in India has been given by Velmurugan et al. (2008) which reveals that the inorganic fertilizer is the major contributor of nitrogen inputs in the ecosystem (10.8 Tg N) followed by manure (1.53 Tg) and a positive balance of 2.32–1.89 Tg N was found which is responsible for various environmental hazards.

A higher positive nitrogen balance (2.5Tg) has been reported in Uttar Pradesh, India dominated with rice–wheat cropping system at an application rate of 180 kg N ha^{-1} via integrated nitrogen application mode (Rao et al. 2017). A higher positive balance of nitrogen in the agroecosystem may cause an influx of reactive nitrogen like nitrate (NO_3^-), ammonium (NH_4^+), and organic nitrogen which may undergo several transformation processes depending on soil moisture status, soil pH, soil temperature, soil surface condition (disturbed or undisturbed), cropping practices, etc. to cause several environmental consequences (Benbi 2017). The values of residual phosphorous deposition have been reported from 0.07 to 1.7 kg P ha^{-1} $year^{-1}$ and may go up to 27 kg P ha^{-1} $year^{-1}$ resulting from non-utilized phosphorous fertilization. Likewise, total sulfur deposition has been reported to be 15 kg ha^{-1} $year^{-1}$ in 1990 in southern Sweden (Singh and Tripathi 2000).

The long-term gain of nitrogen, phosphorous, and sulfur residues into the terrestrial ecosystem will drastically change ecosystem structure and function. Enrichment of these nutrient residues in soil may influence the elimination of some species and may serve as selective advantages for others (competitive exclusion). For example, the composition of peat vegetation was altered due to the phytotoxic load of sulfur causing the elimination of *Sphagnum* species. The resulting community is more simplified due to less species diversity. Some other studies indicate higher species diversity in low to intermediate soil nutrient enrichment. Adverse effects on soil lichen population and sulfur-sensitive higher plants were reported due to sulfur deposition in soil (Singh and Tripathi 2000).

Most of the crops remain unaffected to nitrate concentration in soils until it exceeds 30 mg L^{-1}. But the sensitive crops like sugar beet and grapes may show a considerable decrease in sugar content if nitrate concentration in soils exceeds 5 mg L^{-1}. Delayed maturity and poor quality have been observed in some fruits

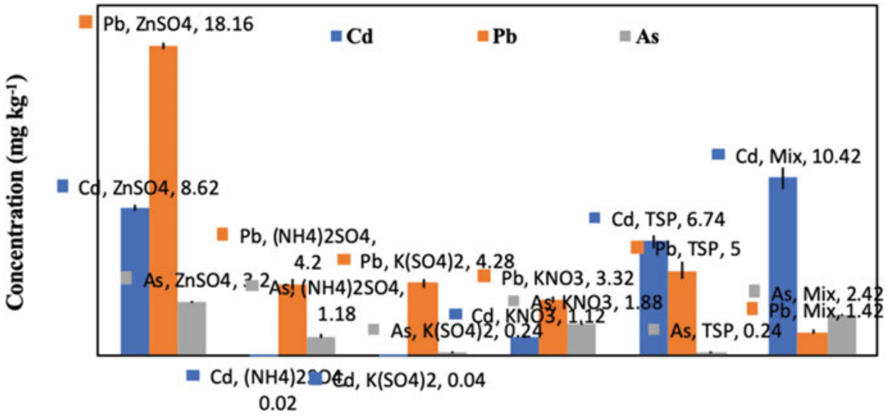

Fig. 4.2 Naturally occurring heavy metal contents of different fertilizers

crops like apricot, avocado, citrus, etc. Grain crops like cereals (rice, wheat, etc.) lodge with excess nitrate load in soil, and consequently the yield and quality are greatly affected (Ayers and Westcot 1985).

Fertilizer nutrients (NPK) influence physical properties of soil by modulating flocculation-dispersion and/or coagulation processes which in turn are dependent on critical coagulation concentration (CCC). CCC refers to the lowest electrolyte concentration at which a soil suspension coagulates or flocculates under a specific set of conditions (Khan et al. 2018). A study has been conducted by Massah and Azadegan (2016) near Tehran, Iran in soil planted with wheat for 50 years continuously and over-fertilized with NPK fertilizers. It revealed that the monoculture nature of crop production with overuse of fertilizers each year increased mineral salt concentration of fertilizers on the soil surface leading to the formation of a compaction layer in the subsoil as evidenced by higher bulk density and penetration resistance. They also found that compact soil led to a decrease in soil porosity, permeability, mean weight diameter, and available water content, which led to the lower solubility of applied nutrients and finally hampered nutrient uptake by the wheat.

Soil chemical properties undergo numerous changes upon excess use of fertilizers like loading with contaminants (heavy metals, radionuclide, etc.) changes in the elemental constitution, alteration of pH, nutrient imbalances, etc. Excess use of fertilizers leads to the accumulation of heavy metals in soil. A study was conducted by Atafar et al. (2010) for 3 years (2003–2005) in different areas of Iran to assess the impact of excessive use of fertilizers by the farmers on heavy metal accumulation in 0–30 cm depth of soil while growing durum wheat. The study revealed the presence of heavy metals naturally in the fertilizers used (Fig. 4.2).

The data showed a maximum amount of As (3.2 mg kg^{-1}) and Pb (18.16 mg kg^{-1}) in zinc sulfate whereas the maximum amount of Cd was recorded in fertilizer mixture (10.42 mg kg^{-1}) and triple super-phosphate (6.74 mg kg^{-1}). They also found the changes of these heavy metals before fertilization and after harvesting of durum wheat indicating that As, Pb, and Cd concentrations increased in the soil after harvesting wheat crop as compared to before fertilizer application. But, the increase was comparatively more for As and Pb than that for Cd.

Among the different chemical fertilizers, phosphate fertilizers are the major sources of traces of heavy metals like cadmium, lead, arsenic, chromium, zinc, etc. (Thomas et al. 2012). A positive correlation between the application of phosphate fertilizer and cadmium accumulation in plants was observed by several researchers (Loganathan et al. 1995; Huang et al. 2004). The heavy metal content of fertilizers individually or due to interactions among each other produce several toxic substances, thereby degrade soil quality, yield, and quality of crops and incur serious threats to animals (Gupta and Gupta 1998). Most of the fertilizers are not acidic, but upon application on soil undergo certain chemical reactions to become acidic and lowers soil pH. Nitrogenous fertilizers (especially, ammonium, ammonia, and urea) upon microbial and enzymatic transformation to nitrate and hydrolysis of urea leave $2H^+$, $1H^+$, and $2H^+$, respectively. Fertilizer-induced soil acidification may occur when the addition of nitrogen exceeds its assimilation by the biotic components of soil or its storage by the soil organic matter. Moreover, the incomplete return of organic anions may also be attributed to the acidification process (Khan et al. 2018). Cai et al. (2015) in their study showed that the pH of the red soil in Southern China decreased from its initial value of 5.7 and stabilized after 12 years of continuous application of N, NP, and NPK fertilizers to its final value of 4.2, 4.5, and 4.5, respectively. Chinese tea plantations with chemical fertilizers recorded significant acidification, as evidenced from 0.47 to 1.43 unit decrease in soil pH in the past 20–30 years (Yan et al. 2020). The type of fertilizer application also influenced the extent of soil acidification. Malhi et al. (2000) studied the effect of nitrogen fertilization at the rate of 168 and 336 kg N ha^{-1} for 15 years on a thin black soil of Alberta, Canada to brome grass (*Bromus inermis* Leyss.). It was found that the soil pH decreased with an increased rate of fertilizer application. They also noticed that the highest extent of acidification was due to the application of ammonium sulfate followed by ammonium nitrate and urea. Soil acidification due to excess use of fertilizers may cause an alternation in the mobility of nutrients and its subsequent availability to plants. Solubility and availability of elements like Al^{3+}, Fe^{2+}, and Mn^{2+} may be increased (Malhi et al. 2000) whereas basic cations like Ca^{2+}, Mg^{2+}, and K^+ may be depleted from soil solution which may adversely affect the normal growth and development of plants. Imbalances of phosphate and zinc availability may also occur in such soil (Khan et al. 2018).

Fertilizer nitrogen application may affect soil organic matter content in two different, more precisely opposite, ways. First, soil nitrogen application at optimum rate promotes crop growth and enhances above-ground biomass and root biomass production. This increased root biomass and part of above-ground biomass (leaf litter, droppings, etc.) may add organic matter to soils as compared to no-nitrogen application. Second, nitrogen application in excess to optimum level leaves residual soil inorganic nitrogen which may accelerate the rate of mineralization of soil organic matter (leaves, straw, litter, etc.) by the soil microbes through the elimination of nitrogen limitation to microbial growth and thus deplete indigenous soil organic matter already present in the soil (Singh 2018). Nitrogen in excess of optimum level may adversely affect soil organic carbon by adversely affecting soil aggregation (Fonte et al. 2009), making previously protected soil organic matter vulnerable to decomposition. However, there is also the opposite view that fertilizer application may promote aggregate formation (Sleutel et al. 2006) and stabilization (Blair et al. 2006) and creates spatial inaccessibility for decomposing organisms (Kögel-Knabner et al. 2008) and thus helps in buildup of soil organic carbon. Overuse of nitrogen fertilizer may also decrease C: N ratio of crop residues and enhance its rate of mineralization leading to reduction of soil organic carbon (Singh 2018). Ladha et al. (2011) meticulously analyzed the entire available long-term data from 114 long-term experiments located at 100 different places across the world to understand the role of nitrogen fertilizer in sustaining organic matter in cultivated soils. Results indicate that no-nitrogen application caused a 7–16% decline in soil organic carbon, whereas, on average, 8% gain in soil organic carbon was recorded in soils that received fertilizer nitrogen.

Soil biological property is mainly characterized by structure (especially, the population of individual or total microbial biomass) and function (soil biological activities like soil respiration, enzymatic activities) of soil microbiota. Both structure and function of soil microbiota get affected by chemical fertilizer application (Marschner et al. 2003). Fertilizers provide nutrients and support directly microbial growth or indirectly promotes microbial growth by stimulating plant growth leading to carbon flow in roots (Buyanovsky and Wagner 1987). However, fertilizers in excess may limit microbial growth by several means like decrease in soil pH and allied nutrient imbalance (decrease of Ca, Mg, and increase of Al concentration), inhibiting enzymatic activities (ligninase, melanoides, etc.) causing hindrance of carbon availability to microbes, increase of the osmotic potential of soil solution, reduction in the investment of fine root biomass, polymerization of polyphenols into “brown compound”, production of harmful reactive nitrogen, etc. (Treseder 2008; Singh 2018). Higher mineral nitrogen and soluble inorganic phosphate concentration in soil adversely affect biological nitrogen fixation by rhizobia and inhibit host infectivity of mycorrhizal fungi (Khan et al. 2018). Considering all these possible ways of growth inhibition of soil microbes due to excess nitrogen fertilization, Treseder (2008) meta-analyzed and synthesized the results of 82 field studies and concluded that microbial biomass declined to the tune of 15% on an average under a heavy load of nitrogen fertilizer. Moreover, the decline in abundance of microbes and fungi was more pronounced in studies of longer duration and a comparatively higher rate of nitrogen application as depicted by the lower response ratio of microbial biomass (fertilized: control), but the source of fertilizer had no consistent effect.

4.4.1.2 Impact on Water Bodies

As nitrate is readily soluble in water, it may percolate down the soil profile with the rain or irrigation water beyond the depth of the root zone and is commonly called nitrate leaching. A study after conducting 16 cycles of maize-wheat-fodder cowpea rotation in loamy sand soil of Ludhiana, Punjab, India revealed that nitrate leaching increases proportionately from 2–3 mg kg^{-1} of soil to 4–5 mg kg^{-1} of soil in 210 cm soil depth when fertilizer application was increased from 50 to 100% NPK, respectively (Benbi et al. 1991). A leached nitrate remains intact after reaching groundwater due to a lack of organic carbon which prevents its denitrification (Bibi et al. 2016). Therefore, leached nitrate pollutes groundwater by increasing its concentration in it which is beyond its permissible limit (50 mg l^{-1} which is equivalent to 10 mg N l^{-1}) (WHO 2004). The major risk of nitrate-loaded drinking water is the occurrence of *methemoglobinemia* in human adults and infants causing loss of oxygen transferring capacity of blood to cell (Bibi et al. 2016).

Nitrate leached from heavily fertilized agroecosystem is also responsible for the decrease in pH (pH less than the range 5.5–6.0) of the contaminating freshwater bodies due to an increase in the concentration of proton (H^+) (Zhao et al. 2014; Bibi et al. 2016). Decreased pH of water bodies disturbs the stability of the aquatic ecosystem by influencing the mobility of various elements. Leached nitrate (NO_3^-) oxidizes pyrites (FeS_x) to sulfate and Fe^{2+} to Fe^{3+} in the subsoil of the aquifer and thereby influences iron phosphate chemistry leading to increased mobility of phosphate in the aquifer; increased concentration of sulfate also catalyzes the anaerobic decomposition of organic matter which is also accountable for increased phosphate availability in the groundwater harvested from the same aquifer (Smolders et al. 2010).

Fertilizers are also the main culprit behind the ecological process called eutrophication. Eutrophication is the enrichment of surface waters with plant nutrients, especially nitrates and phosphates. It causes excessive growth of phytoplankton causing an imbalance of primary and secondary producers of an aquatic ecosystem. Nutrient enrichment of surface waters is caused by runoffs carrying overused fertilizers from agroecosystem (Khan and Ansari 2005). It is known as cultural eutrophication and has been accelerated in recent times (Carpenter et al. 1998). Nitrogen and phosphorous content of moderately eutrophic water has been reported to be 500–1100 μgL^{-1} and 10–30 μgL^{-1}, respectively. The primary productivity, on the other hand, has been mentioned to be above 1 g carbon m^{-2} day^{-1} whereas, for non-eutrophic water, the corresponding value is 0.3–0.5 g carbon m^{-2} day^{-1} (Khan and Ansari 2005). As reported by Lehtiniemi et al. (2005), the major consequences of eutrophication are the occurrence of dense blooms of noxious, foul-smelling phytoplankton which affects water clarity (turbidity), prevention of light penetration into water surface, hindering growth, and ultimately leading to the die-off of plants in littoral zones. It may lead to the production of algal toxins, reduction of biological oxygen demand (BOD), and making the environment hypoxic for fishes and other aquatic lives (Khan and Ansari 2005).

4.4.1.3 Impact on Environment

Indiscriminate use of fertilizers, especially nitrogen fertilizers, will pollute the environment through the emission of greenhouse gases containing a different degree of admixtures of various nitrogen oxides. To a certain extent, ammonia volatilization from added nitrogen fertilizers in calcareous and alkaline soil may also degrade the environment (Savci 2012). Nitrous oxide has a very long life and is about 320 times more potent greenhouse gas than carbon dioxide. It serves as one of the main culprits for ozone layer depletion (Shoji et al. 2001). A comprehensive estimate of area and yield-scaled N_2O fluxes as a function of rate nitrogen application has been documented by Gao and Bian (2017) based on a meta-analysis of individual studies from soils of wheat and maize field of China. Results revealed a higher response ratio (ratio of the weighted mean of N_2O fluxes from soil fertilized with nitrogen to control) of N_2O flux to all the levels of nitrogen application. It indicates that a higher rate of inorganic nitrogen fertilizer, in general, provokes more N_2O emission compared to its no or lower rate of application. In another two-year study in Tezpur, Assam, India, Bordoloi et al. (2019) evaluated the impact of rates of nitrogen fertilizer application on N_2O emission from summer rice fields. They concluded that a 25% reduction of fertilizer nitrogen rate from 60 kg ha^{-1} to 45 kg ha^{-1} enhanced nitrogen use efficiency without affecting yield and resulted in reduced yield-scaled N_2O emission to the tune of 6.0%. Thus, the overall conclusion may be drawn from the illustration that the application of nitrogen fertilizers in excess of the requirement leads to lower nitrogen utilization by the crops causing both area and yield-scaled N_2O emission.

4.4.2 Pesticides and Its Impact

4.4.2.1 Impact on Agricultural Ecosystem

Approximately 25% of global food production is at stake owing to its damage by different pests like insects, disease-causing agents (bacteria, fungi, viruses, etc.), and weeds (Koli et al. 2019). As per Zhang et al. (2018), major pesticides which are used globally include organophosphate pesticides (53.84%), followed by herbicides (25.10%), fungicides, and bactericides (12.06%). Reports say that only 0.1% of applied pesticides will reach the target organisms and the rest amount contaminates the ecosystem in different ways like drift, surface run-off, adsorption in soil colloids, leaching in soils profile, downward percolation to groundwater, phytotoxicity, toxicity to soil microbiota, etc. The degree of toxicity of a pesticide depends on the rate of application, type of pesticide (persistent or nonpersistent), type of soil, nature of crops, management practices, and also weather conditions. Pesticides having a longer half-life (the rate at which the original compound degrades in the ecosystem) will persist long in the ecosystem in its original molecular form and exhibit toxicity. Generally, organochlorine compounds are the most persistent pesticides.

Pesticides affect the population, composition, diversity, and physiological activities of soil microorganisms by changing the quality of soil organic matter, soil pH, and loading soil with undesirable compounds (heavy metals, persistent organic pollutants as an intermediary product of the original compound during the course of degradation). These microorganisms play a crucial role in nutrient recycling and transformation. So, overuse of pesticides may ultimately affect soil fertility. For example, a high dose of imidachlorprid (insecticide) reduced the bacterial population in the soil (Singh et al. 2020). Many reports are available

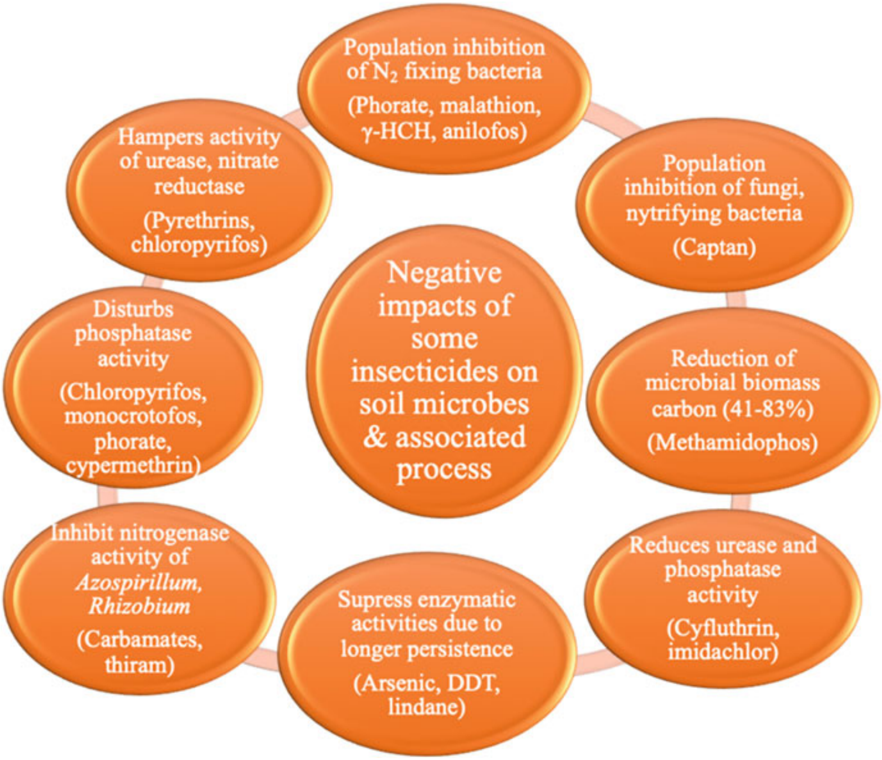

Fig. 4.3 The negative impact of specific insecticides on soil microorganisms, associated processes, and its physiological activities (Source: Mandal et al. 2020; Meena et al. 2020)

showing diverse negative reactions of insecticides on soil microorganisms which are indicated through their reduced population, lower microbial biomass carbon or inhibition of soil enzymatic activities, biological nitrogen fixation, etc. (Fig. 4.3).

The population of nitrogen-fixing bacteria has been adversely affected by most Cu-based fungicides. Overuse of fungicides like apron, arrest, and captan leaves its residue in soil and affects biological nitrogen fixation by altering the population of *Rhizobium* species. Fungicides like mancozeb and chlorothalonil reduce the process of nitrification and denitrification. Organo-mercurial fungicide verdan has a negative impact on cellulolytic fungi of soil when used for a long time in the same field (Meena et al. 2020). Fungicide like tebuconazole, even after short use, may lower microbial biomass carbon and inhibit several fungal activities (Singh et al. 2020).

The beneficial processes of soil microbiota have been influenced by various fungicides (Fig. 4.4).

Herbicides, the other major group of pesticides, also have several adverse effects on soil microbial population, soil enzyme activities, and microbial functions. Some of them are reflected in Table 4.2.

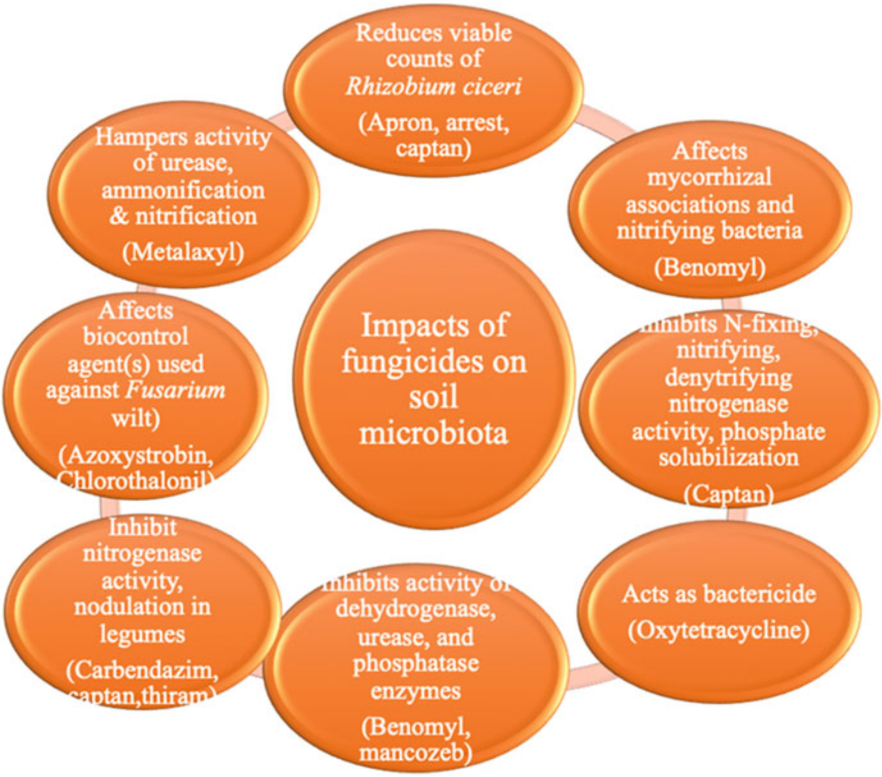

Fig. 4.4 Effect of fungicides on soil microbiota (Source: Meena et al. 2020; Mandal et al. 2020)

The status of earthworms in soils is often used as an indicator of soil quality because its presence or absence often relates to the amount and quality of soil organic matter. The increased concentration of certain herbicides negatively affected the earthworm population. Again, residues of pesticides may remain in soil following its application at higher doses or application of high-persistent pesticides. Some specific examples have been cited in Table 4.3.

Phytotoxicity of herbicides due to its irrational use is another alarming issue of input use in agriculture. Toxic effects of herbicides in plants can be identified by several symptoms like stunting of shoots and leaves, chlorosis, necrosis of leaves, etc. which are mainly caused by the application at a higher rate (Hasanuzzaman et al. 2020). Glyphosate-induced inhibition of seed germination of soybean (Gomes et al. 2017) and delays in seed germination of maize (Gomes et al. 2019) were reported. Zobiole et al. (2011) conducted a study on the inhibitory effect of glyphosate on nutrient uptake of soybean. They concluded that glyphosate affects macronutrient uptake of soybean in the order as follows: Ca > Mg > N > S > K > P, but the micronutrient accumulation follows the order: Fe > Mn > Co > Zn > Cu > B > Mo and Fe > Co > Zn > Mn > Cu > Mo > B. Overuse of herbicide may lead to the

Table 4.2 Impact of specific herbicides on soil microorganisms, associated processes, and its physiological activities (Modified from Meena et al. 2020; Mandal et al. 2020; Singh et al. 2020)

Herbicides	Effects on soil microorganisms and associated activities
Impacts on growth, population of soil microorganisms	
Glyphosate	Activities of *Azotobacter* affected severely
2,4-D	Activities of *Rhizobium* affected severely
Glyphosate, paraquat,diquat, andchlorsulfuron	Reduced the viability of Rhizobium trifolii
Isoproturon	Activities of *Nitrosomonus*, *Nirobacter,* and *urea hydrolyzing bacteria* as well as the growth of *Actinomycetes* hampered badly
Pendimethalin, isoproturon, and fluchloralin	Reduced the survival of *Mesorhizobium cicero*
Atrazine, isoproturon, metribuzin, and sulfosulfuron	Affected *Bradyrhizobium*
Impacts on soil enzyme activities and associated processes	
2,4-D	In purple non-sulfur bacteria, nitrogenase and phosphate reduces with reduced hydrogen photoproduction activities
2,4-D and 2,4,5-T	Through disruption of *Rhizobium* signaling, node-expression is adversely affected. Though its adverse effect on *Nitrosomonus* and *Nitrobacter* and thus on nitrifying processes, 2,4-D reduces fixation by blue-green algae
2,4-Damine, agroxone, and atranex	Azotobacter vinelandii and Rhizobium phaseoli (most sensitive) activities inhibited
2,4-D, Bromoxynil, and methomyl	Reduces methane oxidation to carbon-di-oxide
Metsulfuron-methyl and bensulfuron methyl	Nitrogen mineralization decreases
Bentazone, simazine, and terbutryn	Reduced nodule number in legumes due to the adverse effect on nitrogen fixation
Isoproturon, triclopyr	Nitrate reductase activity hampered badly
Linuron, terbutryn, and methabenzthiazuron	When applied as pre-emergence, nitrogenase activity and nodulation were affected
Glyphosate	Phosphatase activities suppressed significantly
Atrazine, isoproturon, metribuzin, and sulfosulfuron	Reduced nodulation and nitrogenase activity of Bradyrhizobium japonicum
Atrazine, paraquat	Inhibited invertase activity
Cinosulfuron, prosulfuron, thifensulfuronmethyl, triasulfuron	Decreased enzyme activity of arylsulfatase

evolution of herbicide-resistant weeds in both tolerant and GM crops which is irreversible. Moreover, repeated use of the same herbicides on herbicide-resistant crops may exert tremendous selection pressure and help in the evolution of herbicide-resistant weed species. Quick development of resistance by the wide spectra of weed genera against various selective herbicides and easy control of

Table 4.3 Details of residues found with the application of certain herbicides

Name of the herbicides	Details of residue found	References
Metsulfuron-methyl	Residue found in surface soil up to 30 DAS examined through bioassay method, whereas residue detected only up to 15 days following application when examining through HPLC	Paul et al. (2009)
Metsulfuron-methyl	Applied in rice at 30 days @ 2–8 g ha^{-1} left 0.008–0.016 μg g^{-1} residue. But at harvest only 0.001 μg g^{-1} residues were found in soil, grains, and straw	Sondhia (2009)
Isoproturon	After harvesting wheat, the residue of Isoproturon to the tune of 0.006 μg g^{-1} left in soil when applied at the higher dose (2000 g ha^{-1})	Arora et al. (2013)
Clodinafop	After the harvest of wheat, the residue of Clodinafop to the tune of 0.021 μg g^{-1} was found in soil when applied at the higher dose (120 g ha^{-1})	Arora et al. (2013)
Atrazin	The residue of 0.056 mg kg^{-1} of post-harvest soil was found when applied double the recommended rate in maize	Janaki et al. (2012)

complex weed flora lead to over-dependence on nonselective herbicides. Thus, intensive use of glyphosate and concurrent decline in use of other herbicides has created a situation that favors widespread evolution of glyphosate-resistant weeds. Green (2014) has summarized the weeds genus likely to be resistant to several groups of herbicides under different herbicide-resistant crops. He enlisted some prominent dicotyledonous weed genus like *Chenopodium*, *Amaranthus*, *Conyza*, and monocotyledonous genus like *Digitaria*, *Echinochloa*, and *Lolium* having higher chances of developing resistance against Glyphosate, Glufosinate, ALS inhibitors, and Accase inhibitors.

4.4.2.2 Impact on Water Bodies

The major groups of pesticides used in agriculture across the world including India are organochlorine, organophosphates, and synthetic pyrethroid compounds. Pesticides like chloropyripohos, malathion, acephate, and dicofol are mentioned to be highly toxic to fishes owing to its higher potential to run-off and leaching as well as longer half-life (Agarwal et al. 2010). Herbicide residue can also contaminate aquatic ecosystem, especially it has an adverse effect on fishes. For example, bioaccumulation of sulfosulfuron in fish at recommended rates of 25 g a.i. ha^{-1} was studied in a glass aquarium. The study revealed residue of sulfosulfuron in fishes ranging between 1.09 and 3.52 μg g^{-1} after 10 and 90 days, respectively (Sondhia 2008). The sub-lethal concentration of butachlor led to bioaccumulation of the herbicide in liver (0.3515 mg kg^{-1}), gills (0.1255 mg kg^{-1}), and kidney (0.3145 mg kg^{-1}) of *Channa punctata* after 10 days (Tilak et al. 2007). Application of oxyflurofen, anilofos, and butachlor in a rice field located adjacent to a pond caused run-off of herbicide in the pond leading to bioaccumulation of herbicidal residues in fish (Sondhia 2019).

4.4.2.3 Impact on Environment

Application of several pesticides may pollute the atmosphere in the form of drift, production of toxic vapor from volatile pesticides or through photo and microbial degradation of susceptible pesticides. Around 2–25% loss of chemical pesticides may occur in the form of vapor drift which can spread from a few years to several hundred miles and contaminate the nontarget area. Many pesticides volatilize (evaporate from the surface) and reach every part of the environment within a few days. Studies conducted in Indian condition show high levels of pesticide residues in Indian air samples, especially organochlorine compounds. For example, in the tropical coastal area of Southern India, the concentration of DDT and HCH was found to be in the range of 0.16–5.930 ng m^{-3} and 1.45–35.6 ng m^{-3}, respectively (Rajendran et al. 1999). The highest levels of organochloro pesticides (HCHs) were detected in Indian cities ranging from 890–17,000 ng m^{-3} (mean 5400 ng m^{-3}) which was found beyond the highest levels reported across the world (Chakraborty et al. 2010). Considering the environmental adverse consequences, the Indian Government has floated a proposal to review the banning in use, manufacture, sale, and import of 27 pesticides by a gazette notification from the Ministry of Agriculture and Farmers Welfare on May 14, 2020. These are acephate, atrazin, benfuracarb, butachlor, captan, carbendazim, carbofuron, chlorpyriphos, 2,4D, deltamethrin, dicofol, dimethoate, dinocap, diuron, malathion, mancozeb, methomyl, monocrotophos, oxyflurofen, pendimethalin, quinalophos, sulfosulfuron, thiodicarb, thiophanatemthyl, thiram, zineb, and ziram.

4.5 Strategies for Judicious Use of Inputs in Agriculture

4.5.1 Sustainable Resource Management

The concept of sustainability itself is based on the conservation and maintenance of the resource base. In the context of sustainable development of agricultural systems, judicious and scientific utilization of various agricultural inputs are the priority areas. In today’s situation, when most of the resources used in agrarian systems are being threatened by the indiscriminate use and sizable wastages due to lower use efficiency of most scarce resources, it is of prime importance that serious measures should be taken for ensuring better use efficiency as well as conservation-maintenance of the resource base (Baig et al. 2013). In such situations, the emphasis needs to be given to the development of technologies for input saving and increasing use efficiency of inputs in the agricultural systems for a better tomorrow.

4.5.1.1 Conservation Agriculture Practices *vis-a-vis* Climate-Smart Technologies for Improved Input Use

Under the problems of land degradation, water scarcity, increase in climate variability, and the meager scope for expansion of area under agriculture, the agricultural system has to be sustainable and climate-resilient, and it has to meet the food security of the globe. Conservation agriculture (CA) has been perceived as the system which could fulfill the ever-growing demands of food worldwide with the sustainable intensification of crops and various resources (Lal 2015). Actually, CA is a farming system that is designed to hasten the sustainability of the agricultural systems through conserving natural and biological resources in combination with external inputs. Significant concerns throughout the world resulted in higher adoption of CA-based farming practices in the last few decades. The total area under CA worldwide was estimated to be 155 Mha during 2013–14 (Kassam et al. 2014), which increased further to 180 Mha during 2015–2016 spreading over 78 countries having diverse climatic conditions including *Gangetic* plains (Kassam et al. 2018). Not only the resource use and resource degradations but changing climatic scenarios with increased vagaries of weather damaging crops have also become a major driving factor for the adoption of CA. It is not only a resource conservation practice but also a mitigation strategy against environmental damage and a viable answer to the changing climatic scenario.

An overwhelming 600 million tons of residues are produced each year in India and out of them, about one-sixth are being burnt in the field itself owing to serious environmental pollutions, damages to soil biological health, and loss of nutrients (Choudhary et al. 2016). Fair estimates by Jain et al. (2014) showed that residue burning alone causes a loss of 1.5 million tons of plant nutrients in India. These types of ill practices contribute a lot to global warming by releasing CO_2 and N_2O into the environment. In such a scenario, CA provides an economically viable option to retain and manage crop residues to maintain permanent soil cover for agricultural systems with multifold beneficial effects on the production systems. CA is very successful in rice–wheat (R–W) system and many researches carried out over the Indo-Gangetic plains (IGP) in recent years confirmed that CA is beneficial in improving productivity and profitability of R-W system with increased yields, reduced production cost, and improved efficiencies of resource use with better environmental quality (Gathala et al. 2011; Hossen et al. 2018; Jat et al. 2019). Appropriate use of varieties responding to this sort of alternate tillage practices with suitable weed management practices through new herbicides molecules could be explored for further improving the CA systems (Patra et al. 2018; Mitra et al. 2018). Under small holding systems of eastern *Gangetic* plains, increased yields with improved water productivity in rice-based systems were reported (Islam et al. 2019). Unpuddled transplanting has been emerged as a profitable, productive, and energy-efficient system in rice farming to avoid the ill effects of puddling particularly in areas where DSR cannot be done due to climate variability (Islam et al. 2014; Mitra et al. 2018a). Due to the higher use of farm machinery under the CA system, it has been perceived as a technology that can be promoted under labor-crunch situation as labor requirement could be curtailed to 50% *vis-à-vis* huge savings on time, fuel, and machinery costs (Baker et al. 2007).

Enhanced nutrient and water use efficiencies could be achieved through practicing CA systems. Actually, localized placement of fertilizers through drills/planters used for seeding and greater release of nutrients help to increase NUE in CA systems. Higher N use efficiency in wheat with CA-based systems has been reported in many studies conducted in eastern *sub-Himalayan* plains (Mitra et al. 2014, 2019;

Table 4.4 Cost comparisons between conventional and conservation agriculture practices

Name of inputs	Conventional agriculture (USD ha^{-1})	Conservation agriculture (USD ha^{-1})	Saving (%)
Depreciation	115	65	43.47
Fuel	75	25	66.67
Maintenance	22	10	54.55
Agrichemicals	35	45	−28.57
Total costs	247	145	41.30

Data Source: Farooq and Siddique (2015).

Mondal et al. 2018). Bed planting can further improve the N use efficiency *vis-à-vis* apparent N recovery (Devkota et al. 2015) in addition to water savings. Similarly, through surface mulching, run-off can be reduced with a better water infiltration rate which resulted in a 50% increase in water application efficiency (Karki and Shrestha 2015). Experimental studies, as well as modeling-based studies, suggest a striking 20–30% saving of irrigation water with long-term CA (Bhan and Behera 2014). De Vita et al. (2007) have stated that CA reduces the losses of water by reducing run-off and evaporation due to surface residue retention.

CA affects soil organic carbon *vis-à-vis* soil organic matter; higher SOM was recorded in soils under CA systems as compared to soils under conventional tillage practices (Thomas et al. 2007; Muchabi et al. 2014). The difference in soil organic carbon (SOC) between CA and conventional tillage (CT) practices was more prominent and visible under long-term crop rotations (Umar et al. 2011; Muchabi et al. 2014). Despite a large range in C sequestration rates, CA could be perceived as a better alternative through which potential benefits in soil chemical properties and soil environment be harnessed through better recycling of plant nutrients. Soil nitrogen availability has been found to be positively impacted by the increase in the SOC and a general trend of increased soil fertility with an increase in available phosphorus and potassium in CA system has been noted (Mitra and Patra 2019; Sinha et al. 2019). Soil nutrient dynamics as well as internal nutrient cycling are promoted through the CA system, reducing the external nutrient demand of the system and increasing its efficiency.

Adoption of CA minimizes soil disturbance and keeps the soil covered. Thus, it reduces the population of challenging problematic weed *Phalaris minor* and huge consumption of herbicides. Other weed flora in CA systems is generally managed by a single application of nonselective herbicides. However, saving in herbicides may not always be there in CA as reported by several other researchers (Farooq and Siddique 2015). Under the changing climatic conditions, a large area under wheat is regularly being subjected to terminal heat stress resulting in the loss of yield. Adoption of CA in rice–wheat systems can advance the sowing time of wheat at least by 15 days (Malik et al. 2005). Hobbs and Gupta (2004) reported significant yield increase in wheat under CA system from Indo-Gangetic plains. Table 4.4 summarizes the economic benefits of CA achieved through input saving.

4.5.1.2 Site-Specific Nutrient Management for Improving Nutrient Use Efficiency

With the increasing awareness about nutrient pollution worldwide, there is an increasing trend for nutrient research to keep a hold on the losses of the nutrients from the farmland and increase the efficiency of applied nutrients (Roberts 2007). The agriculture sector is facing a major challenge of meeting the world's hunger by keeping pace with ever bulging population and for that, nutrients have to be managed more and more efficiently in the coming days. In the current scenario, the recovery efficiencies of major nutrients lie below optimum and ranged from 20–40% for nitrogen, 15–20% for phosphorus, and 40–60% for potassium fertilizers. Average efficiencies of secondary and macronutrients are even lower and ranged between 5–12% (Rao 2014). Faulty management of nutrients especially the tendencies to apply nitrogen and phosphorus in excess amounts and avoiding potassium, sulfur, and micronutrients have created huge imbalances in many places (Brindaban et al. 2015). Such imbalanced application of nutrients is the prime cause of lower efficiencies (Rietra et al. 2017). Multi-nutrient deficiencies have now become more and more common with less and less application of organic matter into the soil.

Soil systems being highly heterogeneous is thus in need of flexible fertilizer rations based on the location-specific approach. Site-Specific Nutrient Management (SSNM) aims to cater the crops with nutrients as and when they require ensuring higher yield goals (Majumdar et al. 2013). The approach originated from the direct relationship between crop yield and the need of the crop for a nutrient, and a targeted yield provides an estimate of the total nutrient needed by the crop. The portion of this requirement obtained from non-fertilizer sources is referred to as the indigenous nutrient supply. Dobermann and Cassman (2002) have reported a 7% increase in the rice yields and a 12% increase in the profitability in comparison to the farmers' practice from a range of experiments conducted in Southern Asian countries. A study conducted in eastern *sub-Himalayan* plains suggested that nutrient management practice based on Nutrient Expert® in zero-tillage wheat could be considered as a promising option for yield improvement and farm profitability while maintaining the soil health through better nutrient use efficiencies (Mitra et al. 2019). Due to the higher efficiencies of applied nutrients, SSNM can save a significant amount of nutrient inputs. An average of 10–20% reduction in the nitrogen input and 20% and 15% reductions in the phosphorus and potassium input have been reported by Abdulrachman et al. (2002). They have also reported increased nitrogen use efficiency by 12–36%, phosphorus use efficiency by 8–13%, and potassium use efficiency by nearly 100% from transplanted rice fields in Tamil Nadu, India.

Studies across several regions show the deficiency status of soil to secure high yields (Table 4.5). In multi-nutrient deficient soils, restoration of soil fertility in SSNM has been given much priority to sustain the production over the long term. IPNI and Project Directorate of Cropping System Research have also concluded the possibility of a several-fold increase in yield and the possibility of achieving higher yield targets through integrated site-specific management of nutrients (Tiwari et al. 2006). Response to the application of S ranged between 48 and 1350 kg kg^{-1}.

Table 4.5 Multi-nutrient deficiency status of several wheat growing zones

Location	Deficient nutrient status							
	P	K	S	Zn	Fe	Mn	Cu	B
Faizabad	+	+	+	+	–	+	–	+
Jammu & Kashmir	+	+	+	+	–	+	+	–
Kanpur	+	+	+	+	–	–	–	–
Ludhiana	+	+	+	+	+	+	+	+
Modipuram	–	+	+	+	–	+	+	+
Palampur	+	+	+	+	–	–	–	+
Pantnagar	+	+	–	+	–	+	–	+
Ranchi	+	+	+	+	–	–	–	+
Sabour	+	+	+	–	–	–	–	–
Varanasi	+	+	+	+	–	+	+	+

Note: "+" sign indicates presence of deficiency and "–" sign indicates absence of deficiency of a particular nutrient
Data Source: Tiwari et al. (2006)

However, average responses to Zn, B, Mn, and Cu were in the tune of 313, 382, 231, and 173 kg kg^{-1}, respectively (Sharma and Tiwari 2004). Similar findings were suggested by Maiti et al. (2006) from eastern India using Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) approach and SSNM. Partial nutrient balances with SSNM approaches for major nutrients (N, P, and K) in rice–wheat and rice–maize systems were positive for N and P (<50 kg ha^{-1}) but negative for K (up to 90 kg ha^{-1}) under both zero and conventional tillage practices in eastern *Gangetic* plains (Sinha et al. 2019). Efficient uses of fertilizers are required for the long-term sustainability of the farming systems in this agriculturally important region of South Asia which can be achieved through SSNM.

4.5.1.3 Role of Precision Agriculture

It is rightly said that "Knowledge is the power today". In the era of data-driven smart computing, getting information of the existing variability at an even smaller level in agricultural systems as well as their precise management is now possible with precision agriculture (PA) system (Tantalaki et al. 2019). PA is not a single technology or a tool, rather it is the collection of several component technologies aimed at better input utilization efficiency, saving of resources, and increasing the farm profitability as a whole through capturing the variability existing in the system (Jones et al. 2017). Several precision technologies are available today to be used in agriculture for sustainable development purposes. However, their adoption in developing countries is still an existing issue. Efforts for automation of agricultural heavy machineries have started long back in the 1990s. Use of GPS and radio frequency controlled guided traffic in the agricultural systems is long known from the initial years of the 1990s (Choi et al. 1990). Significant advancements have been made for precision guidance systems for agricultural machinery movement in the last few years. Real-Time Kinematic GPS (RTKGPS) is now successfully being used to precisely control machinery movement as well to generate resource application maps for ensuring higher efficiency. RTKGPS-aided tractor mounted sprayers are able to spray very close to target plants (within 5 cm range) at a very high moving speed of nearly 11 kmph resulting in less load on soil, saving diesel fuel, and saving of plant protection chemicals significantly (Abidine et al. 2002). Guided tractor application saved expenses by 2.4% in the seed; 2.2% in fertilizer, and 10.4% in tractor fuel (Bora et al. 2012). Other guidance systems, viz., Autosteer™ and Lightbar™ can reduce diesel consumption by 6.32% and working hours in the field by 6.04% (Bora et al. 2012). Variable Rate Nutrient Application (VRNA) is another component technology of PA that addresses the nutrient demands across the field in real-time and applies nutrients as and when it is required. Such variable rate application is useful to create homogeneity of fertility status over a large field and avoid problems of over or under application of nutrients. Tekin (2010) estimated an increase in winter wheat production by 1–10% with a saving in mineral nitrogen applied ranging from 4–37% with the application of VRNA technology. 6–46% saving in nitrogen has been observed with VRNA technology from a large multisite study in Colorado, USA (Koch et al. 2004). Use of Variable Rate Irrigation (VRI) technology through smart sensor-based real-time estimation of soil moisture and crop water stress resulted in 5–34% saving of irrigation water in multiple cotton fields in Greece (Hydrosense 2013). Variable Rate Pesticide Application (VRPA) allows applying agrochemicals on a need-based precision approach while avoiding spraying at undesired areas (Karkee et al. 2013). There was evidence where it was seen such VRPA technology can save huge pesticides and herbicides (up to 70–90%) for different crops (Solanelles et al. 2006; Dammer and Wartenberg 2007). Variable Rate Planting (VRP) technologies also allow the user to apply seeds/planting materials at a variable rate depending upon the productive potential of specific points across the field. Corn yields have been reported to be increased by an average of 6% with VRS technologies (Hefty 2014).

4.5.1.4 Integrated Management of Pests and Diseases

The ill effects of pesticides in the environment and food systems have been long known from the time of Rachel Carson's "Silent Spring". In the last few decades, the world has seen a huge increase in agricultural pesticide consumption (Sharma et al. 2019). Dependence on only pesticides has created problems like resistance, resurgence, shifting flora, and fauna as well as ecological degradation and environmental pollution. Growing chemical residue in the food chain is another matter of concern today. In order to reduce the chemical load in the production system, Integrated Pest Management (IPM) has been evolved worldwide.

IPM strategy has been adopted by many countries from the 1970s onwards. However, there is still a large technology gap that exists between what is in paper and what lies in the farmers' field (Peshin 2014). India first started research on IPM in 1975 under the Operational Research Project (ORP). The major research findings from ORP were as follows:

- Significant reduction in the pesticide load in rice and cotton through IPM strategy (Sankaran 1987; Pasalu et al. 2004).

- Frequency of pesticide application reduced to two sprays from four to six sprays in rice through IPM (Sankaran 1987).
- 58.6% reductions in the application of active ingredients reported from the cotton fields of Tamil Nadu (Simwat 1994)
- Insecticide application reduced by 12% and 73%, respectively, for the management of bollworms and sucking pests in cotton with the adaptation of IPM (Simwat 1994).

Introduction of Bt cotton in India has greatly reduced the pesticide loads in cotton (Peshin et al. 2007). Despite several initiatives to promote the use of low dose pesticides, banning of several high chemical load pesticides, the introduction of Bt cotton, promotion of IPM, and pesticide usage boomed again after a short initial decrease. It was stated by Dhawan et al. (2009) that pesticides use has increased manifold (39%) during 2011–2012, with per annum growth rate of nearly 5.6%. They further reported a 3–4 times reduction in pesticide load in cotton with proper planning and implementation of IPM. Proper adoption of location-specific IPM strategies holds promises to reduce pesticide load without compromising the efficiency of pest management. IPM strategies are dynamically flexible and demand upgradation and fine-tuning from time to time. Inclusion of new generation chemicals, farm-specific suitable technologies, and farmers' know-how can formulate a very efficient IPM strategy for a sustainable production system (Murray et al. 2005).

4.5.1.5 Agricultural Waste Management for Food Security

Input management must be given due consideration in today's agricultural production system. The agricultural production *vis-à-vis* food security of the coming future is dependent upon the careful management of scarce resources. For better and sustainable management, wastage of inputs must be cut down to enhance efficiency, and side by side byproducts of one enterprise should be reutilized as inputs in other to maintain a closed cycle and reduce wastage significantly (Lin et al. 2013). Several industrial waste products, which are otherwise problematic to be safely disposed of, can be used in the agricultural system as inputs. India produces a good quantity of fly ash from the coal-burning industries but the current utilization of fly ash in the country itself is only 38% (Basu et al. 2009) in comparison to a 100% utilization in countries like Italy, Denmark, and the Netherlands and thus pose greater opportunities to be better utilized. The fly ash is the end residue of coal-burning and thus contains various quantities of minerals that are commonly found in soil. Jala and Goyal (2006) had shown that fly ash on an average consists of 0.004–0.8% N, 0.15–3.5% P, 0.11–22.2% K, 0.1–1.5% S, and various trace elements in sizable quantities, especially 10–3500 ppm Zn and 10–618 ppm B. Apart from being a source of several plant nutrients, fly ash possesses excellent physical properties with 50–60% porosity and 35–40% water holding capacity (Jala and Goyal 2006).

Many researchers have already found the beneficial impacts of the use of bagasse on physical, chemical, and biological properties of soil (Singh et al. 2009; Thind et al. 2012). On average, 200–400 kg byproducts known as steel slag are produced for the production of each ton of steel (Annunziata and Coll 2012) which is known for their basic nature and richness of Ca and Si. Ali and Saharam (2007) reported the use of basic slag in improving plant growth and nutrient availability in acidic soil conditions. Regular application of basic slag increases exchangeable K, Ca, and Mg in soils (Annunziata and Coll 2012). Several other industries produce organic or biowastes which are rich in several plant nutrients and thus can be applied in the field after necessary processing, and at present at the world level, there is about 40% utilization of total sewage and sludge (Matos-Moreira et al. 2012). Use of industrial as well as domestic waste can be successfully managed for the sustenance of the food production system as well as conservation of scarce resources. "Waste to wealth" concept must be employed for reusing inputs, reducing wastes, and closed recycling on resources.

4.5.1.6 Use of Nano-Materials for Better Input Management

Ensuring the sustainability of the agricultural system is a burning challenge to be faced by agriculturists worldwide in which the use of nano-molecules may play a crucial role. Use of nano bionics has shown the potential to increase the catalytic activities of several enzymes used in photosynthesis (Long et al. 2006). It is possible to increase chlorophyll morphology, improvisation of recovery rate from photo-inhibition, and reduction in photo-respiration to increase plant's photosynthetic efficiency through the use of nano-bioengineering (Melis 2009; Evans 2013).

Use efficiency of applied fertilizers is limited by various environmental losses and desynchronized application of nutrients with plant needs. Nano-fertilizer delivery system ensures fewer losses as it synchronizes nutrient release mechanisms with the

Table 4.6 Effect of different nano-nutrition on growth and development of crops

Nanomaterial	crop	Application	Response	References
ZnO	Wheat	Soil application	Increased biomass, grain yield, and higher nutrient use efficiency	Du et al. (2019)
	Coffee	Foliar	Increased net photosynthesis	Rossi et al. (2019)
	Tobacco	Hydroponic	Increased nutrient use efficiency, growth, and metabolism	Tirani et al. (2019)
SiO_2	Rice	Foliar	Increased growth and yield	Rizwan et al. (2019)
	Rice	Foliar	Alleviated heavy metal toxicity	Wang et al. (2016)
Fe	Groundnut, maize	Solid fertilizer	Enhanced growth, yield, and nutrient use efficiency	Disfani et al. (2017)
FeS_2	Chickpea, carrot, sesame, Brassica	Seed priming	Enhanced germination, stress tolerance	Srivastava et al. (2014a,b)

Source: Shang et al. (2019)

plant's needs (Aouada and de Moura 2015). Several nano-fertilizers have been under rigorous experimentation worldwide, some of them are described in Table 4.6.

Apart from nano-fertilizers, recent developments on nano-formulated pesticides show a path for new generation highly efficient nano-pesticides (Bhattacharya et al. 2016). Nano-pesticides are more efficient because of their highly target-specific nature, controlled delivery of active ingredients, and optimum activity due to higher surface activity. Another advancement in the field of agro-nanotechnology is the use of nano-bio sensors. These are analytical devices having at least one dimension below the 100 nm range. Real-time biological data include crop growth, metabolism, disease pest infection, the onset of stress conditions, etc. can be transduced to decision-making systems for higher input use efficiency at whole-farm level (Subramanian et al. 2015). Such advanced technology can make agriculture really data-driven and precision control may be achieved even up to each plant level.

4.5.2 Biotechnological Tools in Reducing Chemical Load

There is the tremendous role of biotechnological and breeding tools in agricultural production and development of the food sector (Estrada et al. 2017) *vis-à-vis* reduction of chemical load in agriculture. Biotechnological tools help in reducing the dependence on chemical pesticides and herbicides. By using the chemistry of living organisms through cell manipulation, biotechnological tools are aimed at the maintenance of better environmental quality (Chen et al. 2005). It is gaining popularity under the context of chemical-dependent agriculture adding pollutants and wastes into the environment. Apart from field crops, even some tree species like poplar have been genetically engineered to avoid heavy metal pollution when grown in contaminated soil (Bagwan et al. 2010). In Europe, the progress of biotechnological tools particularly the development of GM crops resulted in more productive agriculture with a meager impact on the environment through a huge reduction in chemical loads (Zamora 2016).

Though a portion of the world is not accepting genetic manipulation, it is necessary to make the results of these studies known. Still, there are doubts about the health risks of food products developed through genetic engineering. Despite different achievements in this sector since the last 30 years, the acceptance of transgenic food is associated with its possible impact on human health and the environment (Boccia and Sarnacchiaro 2015). It is necessary to demonstrate the benefits brought about by genetic manipulation throughout developing countries where the usage of these products is restricted.

4.5.3 Policy Interventions

Environmental protection and pollution control have become the priority policy issue across the world (Abler 2015). Advancement of innovative production technologies and strong policy interventions are crucial for safe and sustainable agriculture in which appropriate linkages are to be made and strengthened between all stakeholders, viz., government, industries, and academicians. To date, the key government regulatory interventions include the restriction on faulty agricultural practices causing environmental degradation/pollution, prohibition on the sale of dangerous agrochemicals, and controlling the direct discharge of pollutants (Mateo-Sagasta et al. 2017). In the European nations, the legislative instruments have been widely imposed to minimize the environmental degradation from fertilizer sources and fertilizer application (Amann et al. 2017). The significant environmental gains from these administration guidelines are nowadays being prominent, demonstrating that government policy has a crucial role in controlling environmental pollution from agrochemicals. Whereas, in developing countries like China and India, the development and implementation of policies to control agrochemical pollutions are slow and inadequate. In India, this is primarily because of the socio-economic background of the farmers, increased pressure for food production, and existing subsidy policy for fertilizers. In some parts of the country, the current situation is quite alarming. It is estimated that in India about 8% of this subsidy goes to Punjab farmers, cultivating only 2.5% of the cultivated area in the country (Johl 2012). Certainly, in the past few decades, the increased uses of subsidized fertilizers have led to a remarkable increase in food grain production in the country. But the subsidy policy is not much effective in raising farmers' income and has caused environmental damage and serious resource. So, a major paradigm shift in the input subsidy policy is needed to limit environmental degradation such as the poisoning of soils and pollution of air and water from fertilizer sources (Johl 2012). To promote sustainable and eco-friendly products, the Japanese government has made changes in its subsidy program in 2007. To receive payments, producers must be certified as "eco-farmers" which entails reducing the use of chemical fertilizers and pesticides by 50% per hectare compared to conventional farming. The liberal policy packages to the pesticide industry have intensified the indiscriminate use of dreaded agrochemicals. Given the evident adverse implications of indiscriminate use of pesticides, a strong commitment both ideologically and at policy levels must be applied. It is reported that eight states consume more than 70% of the pesticides used in India. As per reports of Times of India (TOI 2019), the industry has grown to be an INR 20,000 crores business in India, with the top three companies having a market share of 57%. The current pesticide regulation act (Insecticides Act 1968) in India has not caught up with postmodern pest management and has many shortcomings which may be amended through the new Pesticides Management Bill 2020. On the other hand, the government's interest to remove ban on GM crop(s) in the country may contribute significantly to reducing the load of toxic pesticides. In developed countries, GM crops (including food grains) are increasingly being cultivated to minimize the load of pesticides. Hence, it is high time to take a strategic step towards the release and cultivation of GM varieties (Datta et al. 2019). The policy instruments have a variable scale of effectiveness at the application level. Therefore, it is always important to assess the impact of the imposed government policies on a specific target. A study was conducted in China to assess the impact of different agricultural pollution control policy evaluation on social, economic, and environmental performance (Abler 2015). The study has reported that the best policy options include subsidies for reducing the use of polluting inputs, education, and technical assistance, subsidies for pollution remediation activities, certification programs, or product labeling.

4.6 Conclusion

Chemical inputs will continue to play a crucial role in agriculture to feed the mammoth population. In several situations, there are more benefits in using chemical input rather than the risk associated with these chemicals. In recent days, many products have been registered with comparatively lesser environmental impacts and the trend has been continued worldwide to restrict the use of older chemicals having severe environmental impacts. Availability of these chemicals at farmer’s doorstep is also to be ensured to reduce the use of older hazardous chemicals. However, there is no evidence that these new chemicals are completely free from residue exposure, acquisition of resistance, and its nontarget effects. In the present context, we may think about integrated management of the soil as well as crops in which a load of chemicals is reduced through integrating the chemicals with bio or organic things with the restoration of biodiversity. We strongly feel that the use of chemical inputs in agriculture should be evaluated not only with respect to its efficiency and cost involvement but also with respect to environmental security, health, and above all the long-term sustainability. More concentrated efforts are to be given on policy and research systems to increase the competitiveness of cost-effective alternatives to chemical inputs. There is a need to enforce policies to address the issues of environmental safety, risk assessment, and behavior of both producers and end users. The basic research on public perceptions and risk assessment may be helpful in the promotion of widespread acceptance and adoption of environment-friendly approaches. We also feel that the provisions of incentives are to be increased for corporate bodies/companies to develop eco-friendly products and at the same time there would be incentives at the farm level for adopting efficient environment-friendly management strategies targeting reduced chemical load.

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5

Agronomic Strategies for Improving Micronutrient Use Efficiency in Crops for Nutritional and Food Security

S. S. Dhaliwal, Vivek Sharma, and Gayatri Verma

Abstract

The micronutrients deficiencies in soil restrain crop productivity as well as decline in micronutrient concentration in crops. In human beings, micronutrients are necessary due to their vital role in various physiological functions. The intensive and exhaustive cropping system, micronutrients leaching, less farmyard manure availability, and conversion of marginal lands for crop production use are the root cause of micronutrient deficiencies in soil. Soil reaction (pH), oxidation–reduction reactions, soil-living organisms, soil exchangeable capacity, and amount of clay are different soil properties controlling the availability of micronutrients in soils. The root hair morphology, root exudation of organic acids, sugars and enzymes secretion, different plant species, and microbial associations are responsible for micronutrients assimilation and its usage from the soil. This article emphasizes the importance of micronutrients in human, animal, and plant systems. The factors affecting the bioavailability of micronutrients and uptake processes of each micronutrient have been discussed in detail. The interrelationships between nutrients in soil and plant systems were also discussed to improve nutrients in soil and its utilization in crops. Biofortification is also discussed to improve the efficiency of nutrients and also

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to deal with global nutritional security. The declines in crop productivity under soil micronutrient-deficient conditions result in human malnutrition. This article will help to explore the soil–crop management systems to improve nutrient use efficiency without affecting environmental quality.

Keywords

Nutrient interaction · Uptake mechanisms · Biofortification · Human and animal health

Abbreviations

Al	Aluminum
As	Arsenic
B	Boron
Ca	Calcium
Cl	Chlorine
Cr	Chromium
Co	Cobalt
Cu	Copper
DTPA	Diethylenetriamine pentaacetate
F	Fluoride
GDP	Gross domestic product
I	Iodine
Fe	Iron
Li	Lithium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Ni	Nickel
N	Nitrogen
P	Phosphorus
K	Potassium
Se	Selenium
Si	Silicon
SOM	Soil organic matter
Ti	Titanium
V	Vanidium
WHO	World Health Organization
Zn	Zinc

5.1 Introduction

Globally, the growing population pressure and environmental degradation have forced the system to focus on food and nutritional security by increasing agricultural productivity. Sustainable agricultural productivity can only be achieved by utilizing and implementing the latest farming techniques to increase agricultural production and by conserving or protecting natural resources (Arora 2018). In spite of an increase in agricultural productivity, there is continuous persistence of multiple forms of nutritional problems across the developing world (Pingali et al. 2017), and implementation of improved agricultural policies has improved nutritional outcomes (Pingali et al. 2015). The food security should be the easy and economic access of sufficient nutritious food for securing the good quantity and quality food for global population (Chappell et al. 2013).

To produce more food, the land base is fixed and under continuous pressure. The intensive cultivation invariably resulted in land degradation, lower soil fertility, and decrease in crop productivity. Healthy plant growth needs essential nutrients but worldwide, most agricultural lands are deficient in one or more essential nutrients.

Micronutrients availability is a major limitation to control crop productivity and quality. In comparison to major food crops, cereals are generally low in micronutrients, and growing them on micronutrient-deficient soils further reduces their concentration in these crops. Intake of micronutrient-deficient cereals affected almost 50% world's population in developing countries (Welch and Graham 2004; Kumar et al. 2021). In India, the content of micronutrients in cereals particularly rice and wheat is generally low due to the imbalanced application of fertilizers which results in depletion of soil native micronutrients reserve (Shukla et al. 2016). Food and nutritional security are also hampered due to micronutrients deficiency. Micronutrient addition in soil lowers the impact of their deficiency in human beings and improves crop uptake (Cakmak 2008). Micronutrient malnutrition has affected nearly one-third of the world population and its deficiencies are difficult to diagnose in human beings, which is often overlooked due to its hidden hunger form. The improved management practices are the best external alternative to improve nutrient use efficiency in soil. To achieve food and nutritional security, there is a dire need to develop and adopt an improved and sustainable production system on a large scale. Better crop nutrition with a high nutrient efficiency for productive and sustainable agriculture is the central point for future food security.

The significance of micronutrients is equal to macronutrients in plant science due to its substantial impact on an array of plant activities (Tripathi et al. 2015; Meena et al. 2020; Dhaliwal et al. 2019b). Plants requirement for micronutrients is small but their role in growth and development is vital. Plant metabolic activities like growth in reproductive parts, synthesis in chlorophyll, carbohydrate production, nutrient concentrations, seed formation, and development of fruits are performed by micronutrients (Tripathi et al. 2012; Kumar et al. 2014, 2018). The adequate level of tracer elements improves the plant physiological activities and other metabolic characteristics; however, the deficiency restricts growth in plants.

Use of modern high-yielding crop cultivars, higher soil erosion, imbalanced fertilizers use, etc. have made micronutrient deficiencies more prevalent in recent years. Major research areas in micronutrients are needed to understand sustainable use of micronutrients, their agroecological complexities in the system, and to harness the full benefits of micronutrients. The biofortification of crops by different methods is required to increase the content of micronutrients in crops (Sandhu et al. 2020; Kumar et al. 2020; Dhaliwal et al. 2019c). The reason for the substantial degradation of agricultural crops in the future is the regular increase of micronutrient deficiency. Considering the importance of micronutrients in plant sciences, there is a need to develop agronomic strategies for improving micronutrient use efficiency in crops for nutritional food security.

5.2 Influence of Micronutrients on Human Health

The entire health and well-being of people are directly or indirectly dependent on the diet of human beings. Food quality is the key to good health, productivity, and longevity. The primary purpose of agricultural production is to ensure food security and safety (Fig. 5.1).

There is little concern about the amount of nutrients or nutritional qualities of food to promote health. In developing countries, failure of the agricultural systems to provide nutritional food for human health is the reason for the silent epidemic of vitamin and mineral deficiencies in people. The deficiency of micronutrients is enormous and affecting globally more than two billion people. (WHO 2002). An

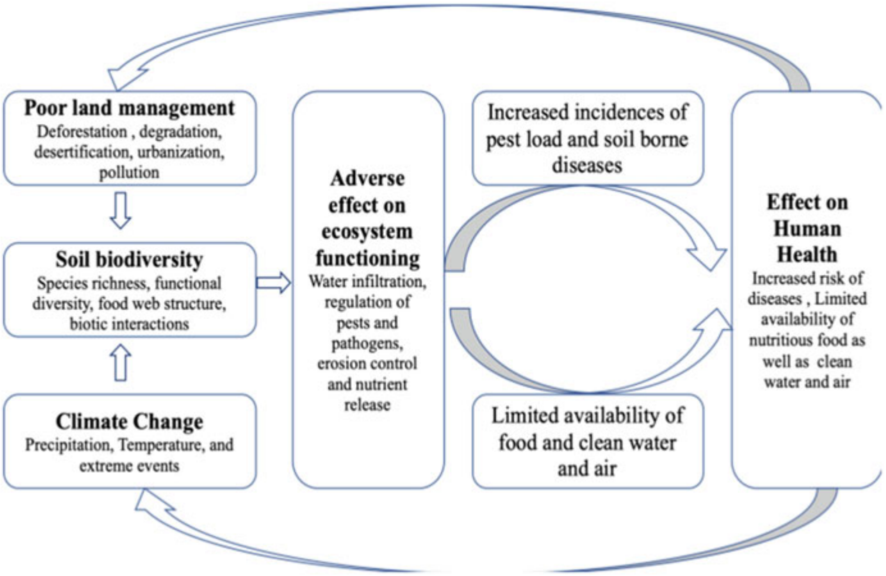

Fig. 5.1 Effect of change in soil biodiversity on human health

inadequate diet of micronutrients in basic foods is responsible for malnutrition. Approximately 1.7 million (2.8%) deaths globally are due to deficiencies of micronutrients caused by low consumption of fruits and vegetables which are considered to be the top 10 most common causes of death globally (WHO 2014). Indian soils registered 49% Zinc (Zn) deficiency,12% iron (Fe) 5% manganese (Mn) 4% copper (Cu), 33% boron (B), and 13% molybdenum (Mo). The deficiency of micronutrients is affecting the European population especially in Eastern Europe, Russia, and Central Asian countries. Fe, Mn, B, Cu, Mo, Zn, Nickel (Ni), and Chlorine (Cl) are eight micronutrients needed for the growth of higher plants in agriculture. Additionally, Selenium (Se), Iodine (I), Chromium (Cr), Florine (F), Lithium (Li), Silica (Si), Arsenic (As), and Vanadium (V) are also required in animals and humans (Welch and Graham 2005). Micronutrients are required by humans throughout life to carry out various physiological functions. The deficiency of micronutrients in the human diet is affecting about 2 billion people globally and results in serious health and nutritional problem (Tulchinsky 2015). A major focus is on Zn and Fe deficiencies which affected one-third of the world's population (Harvestplus 2014). The deficiencies of micronutrients in diet also affect the socio-economic development of human beings (Khush et al. 2012). The deficiency of micronutrients in soils limits crop production as well as human nutrition. As per WHO estimates, micronutrient malnutrition is there in about 3 billion people in the world and nearly 2 billion have a deficiency of Zn and Fe. In Asia, Fe and Zn deficiencies are serious in children of age 0 and 5 years which constitute 35% of the total population. The deficiencies of Fe and Zn result in the unusual stunted growth of children in China (Chen 2000). The health of people entirely depends on the plant's nutrition directly or indirectly. Food satisfaction is the key to good health, productivity, and longevity. In many developing countries, there is a silent epidemic of vitamin and mineral deficiencies due to malnutrition. The World Bank has reported that countries most affected by malnutrition could lose up to 2% of their GDP per year. According to the WHO, Fe, Zn, vitamin A (beta-carotene), selenium (Se), and iodine (I) are the most common biological components of life and among these, Zn deficiency may increase from 49 to 63% by 2025.

Low Zn, Cu, and Mo availability in soils indicate a positive relationship with micronutrient malnutrition in human beings. However, the relationships were less pronounced in Fe. The number of people affected by nutrient deficiency shows lower productivity, decreased knowledge, increased morbidity, mortality, and adverse effect on the immune system (Welch and Graham 2004). Feeding the world's poor with biofortified seeds/edible components can significantly improve targeted nutrient content in humans. The issues are with substances like ascorbic acid and sulfur-containing amino acids which increase micronutrient bioavailability.

The challenge lies in substances (e.g., ascorbic acid) that enhance the diversity in the cropping system and the addition of manures and fertilizers to meet the needs of a healthy diet and are important in reducing malnutrition. The challenge is to meet the Zn need of the human being through Zn-deficient food grains in the existing farming system. With the application of fertilizers, food plants can be enriched with Zn and Fe density and in human beings, its deficiency can be overcome. In poor masses,

Table 5.1 Symptoms of nutritional deficiencies in humans

	Disorder	Deficiency		Disorder	Deficiency
Emotional	Fatigue	Fe	Mouth	Cracked lips	Vitamin B12
	Anxiety	B complex		Weak teeth	Vitamin D, Ca
	Depression	Vitamin D		Sore tongue	B complex
	Poor memory	Vitamin D and B complex		Bleeding gums	Vitamin C, folate
Hair	Dandruff	Omega 3, Se	Nails	Brittleness	Ca, Mg
	Breakage	Biotin Omega3, Vitamin E		Paleness	Biotin, Fe
	Thinning	Biotin, Vitamin D, Zn		White spots	Ca, Zn
Skin	Dryness	Omega3, Vitamin A and E	Muscles	Cramping	Mg, K
	Bruising	Fe, Vitamin C		Numbness	B Complex,
	Inflammation	B complex, Biotin		Twitching	B complex, Mg Vitamin D, Ca
Eyes	Dark circles	Fe	Joints	Clicking	Mn, omega 3
	Poor vision	Vitamin A and D		Swelling	B complex, K

foods with low micronutrients have created health hazards concern about nutritional deficiency especially in developing countries (Graham and Welch 2002). It is important to initiate a study on such global problems with due attentions. According to Food and Agriculture Organisation (FAO) estimates, 50% of the world's cereal crops growing soils are Zn deficient. In India, about 49, 12, 5, 4, 33, and 13% of soils are deficient in DTPA-Zn, Fe, Mn, Cu, hot water-soluble B, and ammonium oxalate extractable Mo, respectively (Singh 2008). Details of mineral deficiencies and their effect on human health are listed in Table 5.1.

5.2.1 Zinc Deficiency

Zinc deficiency in human food has been reported since 1961 and its depletion in humans has been felt in Africa and Asia. More than 90% of Zn implant programs to prevent Zn mortality reduce child mortality by 5% worldwide (WHO 2002; Graham et al. 2001). Estimates of WHO appraised that globally nearly 30% of the overweight children show an increasing trend in Zn deficiency. The crops which are grown in Zn-deficient soils show lower Zn content as compared to those grown in areas with high Zn levels and less Zn deficiency (Bhupal et al. 2009). Zn deficiency in children is associated with allergic illness, eczema, learning difficulties, and hyper-lactation. Zn deficiency also causes anorexia (inability to eat), reversal of growth, ulcers for skin, hard and dry skin, vaccination, no taste, fertility, early birth with low weight, reduces diarrhea in children, and improves bowel movements and diet in children. The recommended safe diet for Zn is 15 μg^{-1} day but WHO (2002) recommended maximum as 45 μg Zn day^{-1}. The consumption of Zn more than 150 μg day^{-1} is dangerous and causes health damage.

5.2.2 Iron Deficiency

Iron deficiency in human beings is mainly due to low Fe content in foods or low-fat diets especially in poor developing countries, especially the consumption of grain foods containing low Fe content and low bioavailability. The prevalence of Fe deficiency, i.e., anaemia is widespread among women and children and acts as a major problem for micronutrient depletion in several parts of India. The distribution of iron content in human body is given in Fig. 5.2.

The 34% of teenage girls in Rajasthan and Gujarat showed the problem of anaemia as severe Fe deficiency (Seshadri et al. 1994). Anaemia is also associated with others diseases like malaria and hookworm infections. The symptoms of micronutrients deficiency in people are anxiety, fatigue, weight gain, decreased appetite, bitter tongue, and angular stomatitis (Table 5.1). The use of folic acid and vitamins as capsules, pills, and syrup, easily available in the market against the Fe deficiency, reduces health risks.

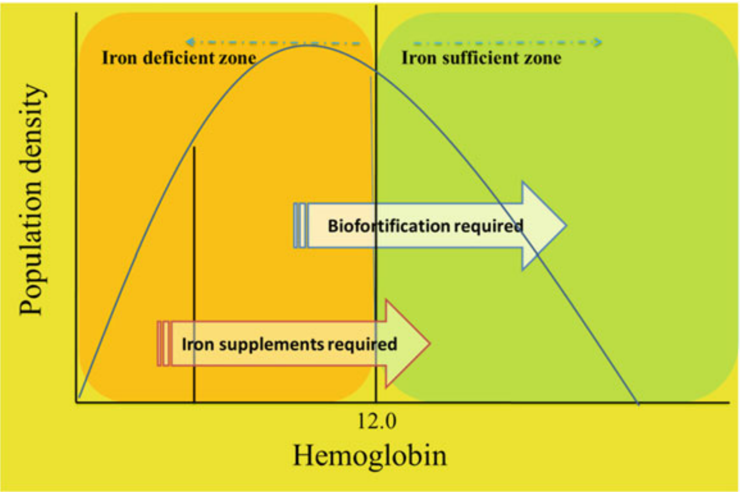

Fig. 5.2 The distribution of Fe adequacy in a population

5.2.3 Copper Deficiency

Micronutrient copper is the fundamental element required by human beings and acts as one of the components in many enzymes involved in reducing oxygen. It is involved in lipid metabolism, bone development, and maturation of the affected tissues. The deficiency symptoms of Cu in humans are anaemia, neutropenia and leucopoenia, bone loss, damage to the nervous system, poor synthesis of melanin pigment (lack of skin color, hair loss), keratinization of the hair, stiff hair, heart disorders, osteoporosis, arthritis, infertility, and diarrhea. For healthy adults, a daily diet of 2 mg Cu^{-1} and 80 μg days^{-1} for children is sufficient (Graham et al. 2001).

5.2.4 Iodine Deficiency

In the world, iodine deficiency (I) is known to cause mental illness. Goitre is the most common form of I deficiency. Parents living in goitre endemic areas have children with cretinism due to iodine deficiency. The recommended dietary intake level of iodine is 150 μg capita^{-1} day^{-1} or 1 mg.

5.2.5 Selenium Deficiency

Selenium (Se) is a component of the enzyme glutathione peroxidase, which helps to protect against oxidative stress. The Se element acts as antioxidants at specific sites which is similar to vitamin E in biological action. “White muscle disease” is the most important disease due to Se deficiency also termed as “nutrient muscular dystrophy”. It reveals chalky white markings, necrosis in skeletal, and heart muscles. It causes hepatic necrosis, oedema of colon, lungs, dystrophy of skeletal, decline in reproductivity, weakened immune responses, and decrease in production of milk and egg. In 1935, “Keshan” development of cardiac disease was identified due to a daily Se intake below 20 mg and the first Se disorder was discovered in 1849 in the mountains and hills of Central China (WHO 1996).

Fortification of food with minerals is a cost-effective sustainable strategy for correcting deficiencies of essential nutrients and reducing health risks. At a national level, cost-effective and rapid fortification of micronutrients for correcting nutrient deficiency disorders in a region should be there. Fortification strategy is successful in many western countries where almost all the processed food is fortified. It involves the modification in the diet system, i.e., food items and patterns. There is also a need to modify the methods using traditional techniques for preparation and processing indigenous food to provide high-quality foods throughout the year. Soaking is a practical, nonenzymatic, traditional method to minimize the phytic acid content of cereals like maize and legumes soybean, green gram, etc. The flours produced from germinated and non-germinated staple foods can be mixed together followed by soaking and fermentation using microbial starter culture for 16–24 h. Then water and flours are mixed to form slurries and cooked to form porridges. Together both have reduced the phytic acid content by 90% as well as enhanced absorption of Zn, protein quality and digestibility, microbiological safety, keeping quality, and reduced toxins like hemagglutinins and cyanide. The soil degradation due to intensive cultivation without proper replenishment of nutrients, limited crop rotations, and minimal application of organics caused poor quality and crop yields and aggravated micronutrients deficiency in soils, crops, and animals worldwide (Shukla et al. 2018). The micronutrients Fe, Cu, Mn, and Zn along with B as well as Mo, Cl, and Ni are essential for plant nutrition, and for animals Zn, Cu, Mn, Fe, Se, I, and Co are essential. In animals, B is a beneficial trace element and prevents Ca and Mg losses from the body.

5.3 Influence of Micronutrients on Animals Health

In plant and animal metabolism, the role of micronutrients is very specific and substitution with other elements cannot mitigate their deficiency. Micronutrients are required for improved health, production of eggs, meat, and milk in animals (Fisher 2008). It is very well recognized that the deficiencies of nutrients in animal diet restricted the growth and productivity of animals. The essential elements Fe, Cu, Mn, and Zn along with Mo, Se, I, and Co play a significant role in animals and each element is involved in the physiological functioning of animal (Table 5.2).

The deficiencies of micronutrients in soils and crops adversely affect animal and human health and their productivity (Shukla 2014; Dhaliwal et al. 2020). In animals, level of micronutrient deficiency affects various physiological processes as these elements are involved in metabolic activities related to growth, reproduction, and health. Subclinical deficiency of micronutrients may cause impairment in reproduction. In terms of soil/plant/animal interfaces, there is often some confusion about "micronutrient". First, an element should have nutritional relevance for livestock and should show physical deficiency signs either "clinical" or "subclinical". Browning of

Table 5.2 Micronutrients, their role in various biochemical processes, and deficiency symptom

Micronutrient	Characteristics	Deficiency symptom/diseases
Fe	Protein and enzyme function. Blood haemoglobin	Anaemia
Cu	Haemoglobin formation, enzyme function, and pigments	Anaemia, poor growth, bone disorders, infertility, brain, and spinal cord lesions. Decolouration of hair
Co	Vitamin B_{12} function and energy assimilation	Poor growth, anaemia, loss of coat, low immunity to disease, infertility
Se	Vitamin E function	Poor growth, white muscle disease, infertility
I	Thyroid gland function	Goitre and reproductive failure
Mn	Enzyme activation	Enzyme activation
Zn	Enzyme function	Stiff and swollen joints, parakeratosis
B	Enzyme function	Weak bones, poor immune function

the hair due to Cu deficiency is a clinical deficiency and diagnosis is very simple. In subclinical signs, symptoms are invisible and fertility loss (Se deficiency) as well as immunity loss to overcome infection (Co deficiency) are more problematic. Deficiencies symptoms are not clear and extreme spreading leads to production loses and even diagnosis is difficult in subclinical signs. The losses caused by the clinical deficiency in animals can be corrected and are short-term whereas subclinical deficiency loss is large in quantum for a longer time. Most of the micronutrient deficiencies generally occurs in ruminants due to limited supply of quality fodders. Every micronutrient has a specific role in the physiological metabolisms of the animals. The micronutrients play a biochemical role in animal systems as enzymes and co-enzymes activities are involved there. "Metallo enzymes" are the enzymes associated with micronutrients (McDonald et al. 1981). The effect of element-wise micronutrients on animal's health is given below.

5.3.1 Zinc Deficiency

In animal body, Zn is found in every tissue and in bones, and the Zn content is more than the liver. High concentration carboxypeptidases of Zn were observed in skin, hair, and wool (McDonald et al. 1981). Zn element is the main component of enzymes pyridine nucleotide dehydrogenases and those which include carbonate dehydratase, pancreatic, glutamic, and dehydrogenase (Plaitakis 2017; Dhaliwal et al. 2013). In many enzymes, Zn also functions as a cofactor. In calves, nose and mouth inflammation are symptoms of clinical deficiency and also includes stiffness in joints, swollen feet, and parakeratosis. Supplementation of zinc leads to improvements in skin conditions which are being seen within 2–3 days. Subclinical conditions which are associated with general "ill-thrift" can be treated with supplements of Zn (Fisher 2008).

5.3.2 Iron Deficiency

In the body, more than 90% of Fe is mixed with proteins and the major component is haemoglobin having 3.4 g kg^{-1}amount of Fe. Fe is also found in transferrin, protein present in blood serum involved in the transport of Fe from one body part to another body part. Fe amount is 200 g kg^{-1}in protein, Ferritin which exists in spleen, liver, kidney, and bone marrow. It is an important part of number of enzymes and some cytochromes including flavoproteins. The major portion of Fe in body exists as haemoglobin; anaemia will evidently result from deficiency of Fe. Haemoglobin is a part of red blood cells (erythrocytes) formed in the bone marrow and are always being "turned-over". The Fe content helps in the formation of new red blood cells by recycling used red blood cells. Fe nutrition requirement is low compared to already present in the body. Thus, Fe deficiency is not common in ruminants and mainly it occurs in pregnant dams and growing young ones.

5.3.3 Manganese Deficiency

The Mn present in the animal body is in limited amount and most often it is in traces. The bones, kidneys, liver, pancreas, and pituitary gland contained the highest concentrations (McDonald et al. 1981). As an enzyme activator, Mn is essential in ruminants and it also activates a number of enzymes like phosphate transferases and decarboxylases, mainly those concerned with the tricarboxylic acid cycle for energy acquisition and utilization like magnesium (Schmidt and Husted 2019). Delayed development, newborns with acute ataxia, defects in the skeleton, and reproductive dysfunction are attributed to clinical Mn deficiency in livestock. Delayed periods of oestrus and conception in cattle and increased abortions are symptoms of subclinical deficiency.

5.3.4 Copper Deficiency

Cu is essential as antioxidant enzymes and lysyl oxidase enzymes which is required for the strengthening of the heart and blood vessels as well as their protection. Cu′s role is important in cardiovascular health. Cu deficiency showed many abnormalities as present in cardiovascular disease. Cu deficiency leads to the development of killer disease (Al-Bayatiet al. 2015). Primarily, Cu plays a catalytic role with many Cu metallo enzymes as oxidases (Harris and Gitlin 1996). Lysyl oxidase is needed for the development of connective tissues including bones, lungs, and circulatory system (Hefnawy and Elkhaiat 2015). Ceruloplasmin is the main cupremic determinant as well as the most sensitive enzyme to Cu deficiency (Hussein and Staufenbiel 2012). Glycoprotein ceruloplasmin acts as an extracellular scavenger in plasma functions and helps in central nervous system functions, and low levels of ceruloplasmin mean more prone to infections and injuries of tissues. Ceruloplasmin also defends the cells from the release of reactive oxygen from neutrophils and macrophages (Picco et al. 2004). Copper is a constituent of many blood proteins. Erythrocuprein is found in erythrocytes (red blood cells), and is responsible for oxygen metabolism. In many enzyme systems, the role of Cu is important as it is a part of cytochrome oxidase, important in oxidative phosphorylation. To prevent hair, fur, and wool pigmentation, Cu is required. Liver is the organ that mainly stores Cu in the body (Fisher 2008).

5.3.5 Molybdenum Deficiency

Mo is an essential nutrient that is necessary for nitrate reduction to nitrite and nitrogen fixation (Williams and daSilva 2002). Mo is needed in higher animals for oxygen transfer reactions of aldehyde oxidase, sulfite oxidase, and xanthine oxidase but it is also connected to a pterion nucleus (Johnson et al. 1980). Under natural conditions, no clinical deficiencies of Mo were reported but certain clinical deficiency reports in animals fed with Mo deficient diets (Anke et al. 1985). The deficiency of Mo resulted in genetic disorders in humans and animals (Reiss 2000). Cu–sulfur–Mo interactions are complex and vary in degree of severity across different species. In most diets, low concentration of Mo is observed but soils with high Mo content resulted in the excess intake of Mo in the plant system. In general, certain areas are found near areas contaminated by mining or smelting operations.

The available Mo content is high in soil and a high concentration in plant system was observed in some localized pockets in the western United States, Canada, England, Australia, and New Zealand. In the areas contaminated with mining and industrial operations, high concentration of Mo in forages has been reported (King et al. 1984). Mo also has an antagonistic effect on the absorption of Cu and availability in animals. Mo is effective on Cu when sulfur (S) is present there. Ruminal microbes produce sulfide from dietary sulfate or organic S compounds. To form thiomolybdate, these sulfides react with Mo and form an insoluble Cu thiomolybdate with Cu (Fisher 2008).

5.3.6 Iodine Deficiency

A very little iodine (I) is required by higher animals and it is used in the synthesis of two hormones produced in the thyroid gland, i.e., tri-iodothyronine and tetra-iodothyronine (thyroxine). In most organs and tissues, these hormones have accelerated responses, basal metabolic rate increase, stimulated growth, and more oxygen intake of the entire animal. Iodine absence allows thyroxine to decrease (Fisher 2008). The deficiency of I causes enlargement of thyroid gland and is known as endemic goitre as well as big neck on farm. The most prominent concern resulting from I deficiency are reproductive abnormalities, dams reproduce hairless, frail, or dead young.

Goitrogenic compounds instigate goitre although when dietary I is sufficient. Iodine deficiency leads to infertility which is difficult to detect in livestock. In some plants belonging to Brassica family (cabbage and rape), soybeans, linseed, peas, and groundnut substances are found. Diets on which livestock are fed should receive Iodine supplementation in significant quantities.

5.3.7 Boron Deficiency

Boron is an essential micronutrient for livestock which is controversial to some extent as its mode of action is not still clear. It has been reported that B is needed in bone formation (Bergman 1981). B levels in low amount can cause brittle bones and joint problems. Plant cells processes are associated with Ca and B with mammalian bone but boron involvement in the physiology of bone directly needs more investigation.

5.4 Environmental Aspects of Micronutrients

Micronutrients are derived mainly from the crust of the earth and are processed for agricultural uses in soil. In agricultural soils, micronutrient deficiencies can be replenished from the total content as mined minerals to available content. The primary sources of micronutrients are soil minerals and organic matter which releases micronutrients to available form by the process of weathering and decomposition. The composition of the parent material is determined by the overall volume of metals present in it. The nutrients exist partly in the solution as soluble ions, free ions, and partly as complexes and bind to organic matter and clay particles. The soil pH, soil organic matter, redox potential, interaction among ions, and soil microorganisms regulate the availability of micronutrients in soils. A global topic of concern is the availability of micronutrients in the soil. The deficient soils replenish the significant demand for micronutrients from the mined minerals and livestock feed supplements.

With the addition of micronutrients and organic amendments, crop yields can increase as well as improve the water use efficiency under water stress conditions (Molden et al. 2010; Dhaliwal et al. 2012). The deficiencies of micronutrients are being aggravated day by day in developing countries due to the non-inclusion of micronutrients in fertilizer schedules and their regular mining by crops (Cakmak 2009; Jones et al. 2013; Yadav et al. 2020). Most micronutrients do not show their toxicity in agricultural fields, because of reduced supply of micronutrients to plants. Interaction of nutrients, organic matter, geomorphology of soils, parent materials, and microbiology of soils determine micronutrients supply to plants.

Phosphates and carbonates also associate with some micronutrients to form chemical precipitates, also interact with clay colloids and mineral complexes, and reduce their availability to the crops (Allen 2002; Marschner 2012). The bioavailability of specific micronutrients is also influenced by plant roots. Some specific plant roots may extract soil micronutrients by dissolving fixed minerals through extensive root systems, excretes exudates, organic acids, and phytosiderophores (White et al. 2013; Keuskamp et al. 2015). One of the possible reasons for deficiency of micronutrients in human beings is low nutrient use efficiency by crop (Baligar et al. 2001; Kaur et al. 2020). The continuous extensive rice–wheat cropping system in India over the years leads to high crop yields but also depleted micronutrients from the soil. The extent of micronutrients availability such as Zn and Mn has become limited for crops and resulted in malnutrition of humans and animals (Cakmak 2009; Monreal et al. 2015).

The Zn solubility and its availability to plants are regulated by the adsorption–desorption process (Alloway 2004). The higher Zn uptake and better mobilization of plant Zn reserves towards grain resulted in higher uptake due to Zn fertilization (Hussain et al. 2016). The agronomic biofortification alleviates some of the challenges of micronutrients deficiencies in soil for crop production quantitatively and qualitatively.

Deficiencies of minerals occur due to their inadequate replenishment to soil from the parent material and adsorbed complexed fractions. The natural factors, soil pH, human activity, and soil depletion due to extensive farming without adequate fertilization also resulted in a deficiency of nutrients in agricultural soils (Dhaliwal et al. 2010, 2017). The deficiency of micronutrients in the soil is a worldwide problem, however, the extents vary from nutrients to nutrients and place to place (Voortman and Bindraban 2015). In India, the deficiency of micronutrients is a severe problem in light-textured and calcareous soils. In rice–wheat cropping system with coarse texture, micronutrients deficiency is a severe problem. Initially, Fe deficiency in rice crop is noticed and later Mn deficiency in upcoming crops. Micronutrients deficiency in soil is not only limiting crop yields but also affects animal and human health. In intensively grown crops, specifically cereals, oilseeds, pulses, and vegetable crops micronutrient deficiencies are frequently observed these days. The deficiency in Zn, Fe, Mn, Cu B, and Mo in Indian soils were reported to be 49, 12, 5, 3, 33, and 11%, respectively (Singh, 2008). The most suitable methods to correct the micronutrients deficiency in crops are soil and foliar application for Zn, B, and Mo, however, the only foliar application is recommended for Fe and Mn in crops.

The micronutrients availability in Indo-Gangetic Plains (IGP) were reported to be low due to exploitive cropping system involving crops rice–wheat, NPK fertilizers use disproportionally, and little addition of micronutrients (Sidhu and Sharma 2010; Dhaliwal et al. 2015; Shukla et al. 2016). Excessive phosphate fertilization in soil also resulted in micronutrients deficiency. Phosphate restricts the availability of Fe, Zn, and Cu for crops. Mo is essential for nitrogen fixation by legumes and its limited supply leads to nitrogen deficiency and reduces crop yields. The deficiencies of Zn and Cu are severe in crops grown on calcareous or alkaline soils, particularly in arid and semi-arid environments. In India, nearly half of the agricultural soils as well as in Turkey, and in China one-third agricultural soils and most of the soils in Western Australia exhibit Zn deficiency (Broadley et al. 2007; Ismail et al. 2007). Owing to small diffusion coefficients and lower concentrations of Zn^{2+} and Cu^{2+} in the soil solution these ions possess restricted mobility in the soil (Broadley et al. 2007; Cakmak 2008) and plant roots must feed through the soil to obtain adequate Zn and Cu for plant nutrition (Hacisalihoglu and Kochian 2003).

Nowadays soil application of micronutrients through chemical fertilizers is getting popularised but is expensive and limited to specific soil conditions (White and Broadley 2009). The integrated nutrient management practices regulate micronutrient supply in soil–plant systems thereby reducing the micronutrient deficiencies in cereal-based cropping systems (Walia et al. 2010; Dhaliwal et al. 2015; Khaliq et al. 2017). The nutrient management using organic manures improves micronutrient availability through mineralization (Khaliq et al. 2017) and facilitates their transfer in soil–plant system (Moharana et al. 2017) by using different mechanisms (Wang et al. 2012). Erosion and leaching in soil are also responsible for micronutrient deficiencies in soil and management of erosion and leaching in soil increases micronutrients in soil. The soil adsorption complex is the most significant buffer for free and dissolved ions. Soil pH, moisture content, temperature, and nutrients interactions are the key factors for the release of ions in soil. In addition, soil biology especially the mycorrhizas also play important role in release of micronutrients from unavailable to available pools. The vast mycelium interactions with the mineral deposits and nutrients are absorbed usually in forms that are not accessible to plants.

5.5 Sources of Soil Micronutrients

Plants only absorb the nutrients which are present in soil solution or in the chelating forms. The micronutrients in the soil solution undergo a rapid change with phosphates and carbonates present in the soil to form chemical precipitates (Wall et al. 2015). The micronutrient availability in the soil also varied with the availability of clay, mineral, and organic matter complexes present in the soil (Dhaliwal et al. 2008; Dhaliwal et al. 2012). The availability of micronutrients in soils is regulated by the soil pH, soil redox potential, soil organic matter, concentration of coexisting elements, and soil microbial population present in the soil. Micronutrients are released from unavailable pools (primary and secondary minerals and organic matter) to available pools through weathering and decomposition (Fig. 5.3).

Micronutrient concentrations varied with the rock and minerals. Among different micronutrients, Fe, Mn, and Cu concentrations are higher in igneous rocks than in sedimentary rocks, and contrary (Table 5.3), B concentration is higher in sedimentary rock (Bowen 1979). Molybdenum and B concentrations are higher in effusive rocks compared to plutonic rocks. Micronutrient concentrations in soils are affected

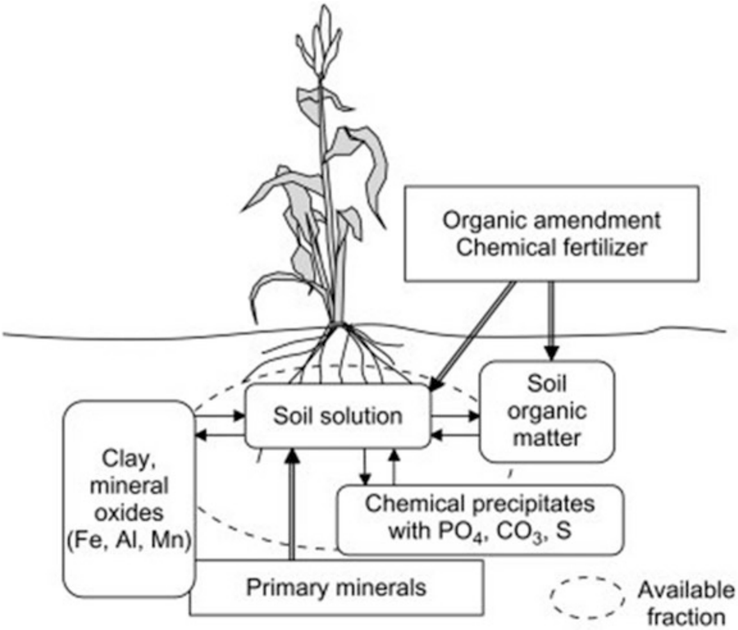

Fig. 5.3 Availability of micronutrients in soil solution from different sources (Source: Masunaga and Fong 2018)

Table 5.3 Relative stability of minerals and their associated trace elements

Degree of stability	Mineral	Major constituents (except Si, O)	Minor constituents
Stable	Tourmaline	Ca, Mg, Fe, B, A1	–
	Magnetite	Fe	Zn
	Ilmenite	Fe, Ti	–
	Muscovite	K, A1	(B)
	Orthoclase	K, A1	Cu
	Garnet	Ca, Mg, Fe, A1	Mn
	Albite	Na, A1	Cu
	Oligoclase	Na, Ca, A1	Cu
	Andesine	Ca, Na, A1	Cu, Mn
	Anorthite	Ca, A1	Cu, Mn
	Biotite	K, Mg, Fe, A1	Mn, Zn, Cu, (B, Mo)
	Augite	Ca, Mg, A1	Mn, *Zn,* Cu
	Hornblende	Mg, Fe, Ca, A1	Mn, Zn, Cu
Easily weathered	Olivine	Mg, Fe	Mn, Zn, Cu, Mo

by types of parent materials and soil formation/degradation processes. Organic material serves as a major secondary source of some micronutrients. Animal waste has a higher content of micronutrients compared with plants or other livestock feeds. The sewage sludge contains high levels of Cu, Fe, and Zn. These OMs can be applied as micronutrient amendments to soils.

5.6 Micronutrients in Plant System

Micronutrients are needed by plants in very small quantity and their general requirements are 100, 50, 20, 20, 6, 0.1, and 0.1 mg kg^{-1} of dry matter for Cl, Fe, Mn, B, Zn, Cu, Mo, and Ni, respectively. The deficiency symptoms appear in plants or enter into hidden hunger when the concentrations of micronutrients are below their respective critical concentrations. The plants due to deficiency of micronutrients resulted in impairment of biological and physiological functions. In order to understand the chemistry and availability of micronutrients in soil, it is important to know the specific functions of each micronutrient in plant system. Micronutrients cations in soil generally occur in the divalent form (Fe may also be trivalent) and are subjected to strong adsorption on negatively charged clay and humus. The nutrients proportion required by the plant system depends on its life cycle, environmental conditions, and its genotype. The addition of micronutrients also improve the content of other nutrients in the crop as positive interaction (Dimkpa et al. 2015; Rietra et al. 2015; Dhaliwal et al. 2019b).

The uptake of nutrients by plants is a selective process due to which nutrients ratio is not the same inside the plant as it exists in the soil. In the absence of any micronutrient, the processes that drive plant metabolism of other macro- and micronutrients would not be optimally functional. The reliable measurements of micronutrient fluxes across membranes are necessary for a better understanding of micronutrient transport in plant systems. The low internal requirements for these elements will be low as compared with the macronutrients. Mineral elements in plants are acquired in specific chemical forms. The knowledge of bioavailable forms of mineral elements acquired by plant roots, and their limitations in the supply and phytoavailability is necessary. The supply and phytoavailability of mineral elements govern the accumulation of mineral elements in plants. The cationic forms Fe, Zn, Cu, Ca, and Mg were taken by the roots of plant species and some plants also take as metal chelates (White et al. 2013). The plant-available forms of selenium are selenite, selenate, or organ selenium compounds (White et al. 2009; Li et al. 2008).

5.7 Micronutrients' Uptake Mechanisms

Nutrient uptake by plants involves the accumulation of higher concentrations of nutrients inside the plant cell than in the surrounding medium, with few exceptions which involve electrochemical gradients and driving forces. Active uptake is usually interpreted as the movement of a nutrient against its electrochemical gradient. The uptake of ions is possible through passive mechanisms which might be due to energy expended by electrogenic pumps in setting up the voltage gradient. Various plant mechanisms for uptake of different nutrients have been discussed below.

The plant roots generally absorb Zn as a divalent cation (Zn^{2+}ion) and in some cases, as organic ligand-Zn complexes. The two physiological approaches are involved in divalent cations uptake like Zn^{2+}ions by the plant roots. Approaches involve Zn complexes (Zn phosphates, hydroxides, etc) solubility through reductants efflux, productions of organic acids and H^+ ions, and root epidermal cells absorbs the Zn^{+2} in soil solution. The organic acids (citric acid, malic acid, oxalic acid, tartaric acid, etc) are released by the root exudates/mucilage or epidermal cells. Strategy II involves the efflux of phytosiderophores which form stable complexes with Zn. These complexes are subsequent absorbed by the root epidermal cells especially in cereal roots. Phytosiderophores are non-protein amino acids with low-molecular-weight organic compounds which have high binding affinity for their respective metals. Zinc absorption as Zn^{+2}occurs through mass flow and diffusion mechanisms by roots.

This uptake mechanism in plants varies from species to species (Graham et al. 2001). The crop sensitive to zinc deficiency is maize however the wheat genotypes show variable responses to Zn nutritional stress. Among different forms of Zn, water-soluble, labile Zn, and soluble organic complexes are the plant-available forms of Zn. (Alloway 1995). Excess of Na, Ca, and Mg in soil, high amounts of carbonate/bicarbonate content, and the low amount of organic matter affects Zn availability in soil (Fig. 5.4) (Lindsay 1972).

Zinc transmission in roots is regulated by the pH of soil and moisture content in soil (Marschner 1993). Under high pH conditions in soil, zinc is hydrolyzed as Fe oxide (FeO) and gets co-precipitated (Alloway 1995). The decreased Zn concentration in soil solution was 45% with the increase in pH from 5.5 to 7.0 (Marschner

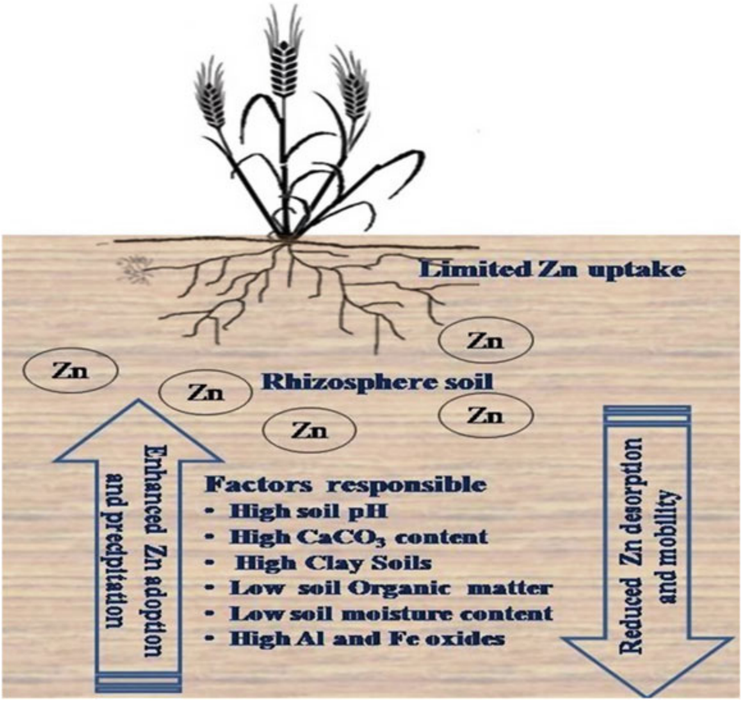

Fig. 5.4 Major factors affecting availability of Zn to plant roots

1995). However, at higher soil pH (>8.0) FeO coating around carbonate minerals aggravated the Zn availability in calcareous soils.

Phosphorus fertilization also influences Zn availability. The higher application of phosphorus decreases the Zn concentration in grain by 17–56%. (Zhang et al. 2012). Phosphorus application decreased Zn concentration in wheat in field and glass house conditions (Zhang et al. 2012). Actually, the P content in shoot is accumulated without antagonistic effect of Zn, which resulted in decreased Zn concentration at cellular level due to dilution effect (Loneragan et al. 1979). The negative effect of P on soil Zn availability was corrected by association with mycorrhizae as it favors Zn absorption with its extended rooting system (Ova et al. 2015). This mutual symbiotic association between a plant and fungus helps plant roots to increase the surface area, which explores large area for water and nutrient utilization (Subramanian et al. 2013). The morphology of roots is improved and enhanced the nutrient uptake to withstand seasonal stress (Subramanian et al. 2008). Zn phytate is amongst organic compound which is quiet common which bind the Zn within the root cells and responsible for Zn translocation within plant. The Zn phosphate synthesis in apoplast cells of root also resulted in non-uniform distribution of Zn in plant system (Dhaliwal et al. 2019a). The Zn-efficient rice genotypes have a greater potential to translocate Zn from older to actively growing tissues than Zn-sensitive rice

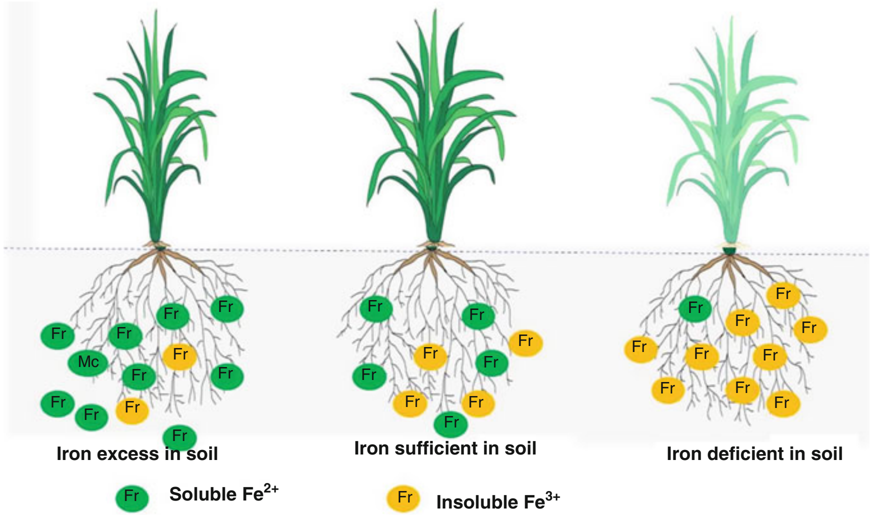

Fig. 5.5 Iron transport system in plants

genotypes (Impa et al. 2013). Sperotto (2013) and Dhaliwal et al. (2019c) reported that in Zn sufficient condition, root uptake during grain filling stage results in Zn accumulation in rice grains, however uptake through root and remobilization though leaf tissues contribute equally to grain Zn under Zn-deficient conditions.

Iron as essential plant nutrient play important role in various plant growth processes, i.e., respiration, chlorophyll biosynthesis, and photosynthesis. The solubility of Fe is extremely low under aerobic conditions with soil having a higher pH range. Therefore, plants have developed different efficient iron-uptake mechanisms for iron uptake (Fig. 5.5). Iron is prone to precipitation and higher ionic iron concentration in soil solution as toxic. Plants have refined internal iron-transport mechanisms which include iron chelates including nicotianamine, mugineic acid family phytosiderophores, and citrates. To maintain iron homeostasis in the system, plants have developed mechanisms for regulating gene expression in response to iron availability.

Boron is taken by plant as boric acid, which is relatively permeable across biological membranes. Boric acid is a small, uncharged molecule (Dordas et al. 2000; Stangoulis et al. 2001). The plant absorbs B through passive diffusion of boric acid. However, in case of limited availability, plants utilize BOR family of borate exporters and boric acid channels for B transportation in the plant body. Under B toxicity conditions, plants use BOR borate exporters for B exclusion from tissues (Schnurbuch et al. 2010). The transport and homeostasis of B are mainly based on three transport mechanisms across the plant membrane: (1) passive diffusion of boric acid across lipid bilayers, (2) facilitated diffusion of boric acid, and (3) export of borate, which is formed in cytoplasm with boric acid. With the lower pH in the apoplast, there is rapid change in borate anion to uncharged boric acid and thus results in the generation of BORs as uphill gradient of boric acid. B is highly mobile and preferentially transported to growing tissues under limited available B conditions in the soil. The B mobility in phloem is highly different among plant species. In sucrose-producing plant species, the formed complexes in the plant system reduce leakage of B from the phloem (Stangoulis et al. 2010 and Singh and Singh 2020).

Kannan and Ramani (1978) studied the active uptake of soil applied Mo by roots and it's transport to plant system. The Mo uptake in plant system and intracellular Mo sensing levels are well-controlled processes and take 6 hours for maximum concentration in plant shoot after Mo application. Mo is a highly mobile compound in plant system and is translocated between various plant tissues. The sulfate content in soil is an effective inhibitor of Mo uptake and low sulfate content in soil stimulates the Mo uptake (Shinmachi et al. 2010).

5.8 Factors Affecting Micronutrients Availability

There are many factors, i.e., pH, SOM, temperature, and moisture, which are responsible for the availability of micronutrients in soil and uptake to crop plants. The degree of effectiveness of these factors and their relationship among nutrients vary from nutrients to nutrients. Soil pH strongly affected the availability of micronutrients. The Zn, Fe, Mn, and Cu in plants decreases broadly with the increase in soil pH; however, the availability of Mo and B increases with increase in soil pH Available content of Co, Cu, Ni, and Zn in soil increases with the increase in clay content in soil (Lee et al. 1997).

5.8.1 Soil pH

Soil pH influences ionic form, mobility, and solubility of micronutrients in the soil as well as their availability to plants (Fageria et al. 1997). There is a decline in the availability of micronutrients, i.e., Zn, Fe, Cu, Mn, B, etc., and increase in Mo availability with increasing soil pH (Table 5.4). These micronutrients are usually adsorbed on the sesquioxide on soil surfaces. Fe solubility decreases 1000-fold with every unit of soil pH increase and about 100-fold decreases for Mn, Cu, and Zn, respectively (Lindsay 1979; Sharma et al. 2007). The soil pH has a direct effect on Zn mobility and availability in soils and Zn availability decreases with increase in soil pH (Anderson and Christensen 1988; Saeed and Fox 1999). The adsorption of Zn as hydrous oxides of Fe, Al, and Mn with the increase in soil pH >5.5 (Moraghan and Mascagni 1991). The pH above seven forms Zn $(OH)^+$ in soil; however, the OM solubilization increases Zn content in soil solution (Barber 1995). In acidic soils, an increase in single unit of soil pH between 5.0 to 7.0 decreases 30 folds in Zn concentration (McBride and Blasiak 1979). Zinc absorption in wheat has an inverse relation with H^+ concentrations, which could be the secondary effects of nutrients

Table 5.4 Influence of soil pH on micronutrient concentrations in soil and plant uptake

Element	Content in soil and plant uptake	Element	Content in soil and plant uptake
Zn	Zn solubility decreases by100-times with each unit increase in pH. As a consequence, it affect the plant uptake	B	Increase in soil pH favors adsorption of B. availability and uptake of B decrease dramatically at pH >6.0
Fe	Ferric (Fe^{3+}) and ferrous (Fe^{2+}) activities decrease by 1000 and 100-fold in soil solution, respectively with each unit increase in soil pH. In oxidized soils, Fe uptake by crops decreases with increase in soil pH	Mo	Soil pH above 4.2, $MoO4^{2-}$is dominant. Concentration of Mo increases with an increase in soil pH and increases plant uptake. Water-soluble Mo increases six times/with an increase in soil pH from 4.7 to 7.5
Mn	The ionic form of Mn in soil solution as Mn^{2+}, decrease by100-fold for each unit increase in soil pH. In extremely acid soils, Mn2+ solubility cause toxicity problems to some crop species	Cl	Chloride is bound tightly in mildly acid to neutral pH soils and it becomes negligible at soil pH 7.0. In Oxisols and Ultisols, Cl adsorbed with increasing soil acidity which is dominated by kaolinite clay. Increasing soil pH generally increases cl uptake by plants
Cu	The solubility of $Cu^{2+}$is pH-dependent and it decreases 100-times with a single unit increase in soil pH		
Ni	Ni^{2+} is relatively stable with wide ranges of soil pH and redox conditions. However, availability is generally higher in acidic than in alkaline soils. At soil pH ≥7, retention and precipitation increase. Increasing the pH of serpentine soils through liming from 4 to 7 reduced Ni in plant tissue		

Source: Fageria et al. (1997)

take up and competition of Zn^{2+} and H^+ at root surface (Chairidchai and Ritchie 1993).

The Cu content increases with pH varying from 4 to 7 and gets specifically adsorbed in soil as Cu^{+2} ions with clay minerals (Cavallaro and McBride 1984). The readily soluble Cu (exchangeable or adsorbed) decreases with the increase in soil pH (Alva et al. 2000) and over liming in acidic soils also leads to Cu deficiency in soil. The SOM plays a crucial role in Cu adsorption and also with readily Cu complexes. For Mn, increase in soil pH in sandy soil increased organic fractions of Mn (Shuman 1991). The reduction of Mn^{4+} to Mn^{2+} is higher at low soil pH. Soil with pH less than five results in Mn toxicities in sensitive plant species (Mortvedt 2000). Mn content in soil solution increased 1.6fold for each unit decrease in soil pH in well-drained Mollisol soil with the application of high N fertilizer (Fageria and Gheyi 1999). The available content of Mn, Cu, and Fe is generally higher under submersed or flooded soils (Ponnamperuma 1972).

Among micronutrients, B is the only micronutrient to increase concentration in soil solution with the increase in soil pH. Decrease in soil pH decreases the availability of B due to adsorption of B on clay and Al and Fe hydroxyl surfaces (Keren and Bingham 1985).

Molybdenum is available as $MoO4^{2-}$ and the availability of Mo generally increases with increases in soil pH. The acidic conditions in the soil lead to the low availability of Mo (Kabata-Pendias and Pendias 1984). High soil pH increases the solubility of $CaMoO_4$ and H_2MoO_4 (molybdic acid). The sorption of Mo on Fe oxides increased with decreases in soil pH from 7.8 to 4.5 (Hodgson 1963). The adsorption of Mo was maximum at pH <5 with Al and Fe oxides and it decreased with the increase in soil pH (Goldberg et al. 1998). Hydrous Fe and Al oxides adsorption on Mo decreased with the increase in soil pH and increases the Mo solubility and availability to plants (Williams and Thornton 1972). Biback and Borggaard (1994) also reported that at pH 3.5 Mo adsorption was maximum on Al and Fe oxides and declined as soil pH increased.

The Ni solubility is moderate to high in soils of acidic nature and decreased with an increase in soil pH. The content of exchangeable and soluble Ni^{2+} is higher under acidic conditions and Ni absorption on oxides, non-crystalline alumina silicates, and layer silicate clays increased with the increase in soil pH >6 (McBride 1994).

5.8.2 Soil Organic Matter (SOM)

Soil organic matter is classified as water-soluble and water-insoluble compounds. Fulvic acids are water-soluble compounds with higher molecular weight; however water-insoluble compounds are humic acids or humin compounds comprised of anionic oxygen groups including aliphatic carboxyl, phenolic hydroxyl and carboxyl, alcoholic hydroxyl (Tate 1987). Humic acids form ionic bonds or complexation reactions with metals (Stevenson 1986). Strong metal complexes or ionic bonding are in low-molecular-weight organic acids (acetic, citric, malic). Organic matter increases Zn availability in soil by the formation of soluble complexes with organic, amino, or fulvic acids. Insoluble Zn–organic complexes with SOM are also formed which affect Zn solubility. The exudation from roots and microbes mineralizing Zn forms complexes in rhizosphere and increase the availability of Zn to plants (Lindsay 1972).

Iron content in soil forms stable complexes with organic compounds (Barber 1995). The soluble Fe forms complexes with organic acids such as citric, malic, oxalic, and phenolic when releases on decomposition of SOM (Lindsay 1991). Bioavailability of Fe is more affected by soil pH than the SOM content. The soil Fe forms the most stable complexes, Fulvic and humic acid, as compared to other nutrients. The effectiveness of these stable complexes varies with soil pH (Stevenson 1991). Adding OM in the soil improved Fe availability under aerobic and submerged conditions in soils (Tisdale et al. 1985). The Mn availability to crop plants did not show any significant variations with the addition of SOM content (Reisenauer 1988). Among different Mn fractions, water-soluble, exchangeable, and organically bound fractions are important to plants. The Mn availability in soil is closely associated with SOM (McDaniel and Buol 1991). Complexation of Mn^{2+}ions with fulvic acids, humic acids, and humins as well as with amino acids, hydroxamates, phenolics, and siderophores (Marschner 1995). Soil OM shows little effect on the availability of Mo as it gets fixed. Organic matter remarkably improves the mobilization of Mo under impeded drainage conditions (Fagaria et al. 2008).

In acidic soil, OM acts as the primary source of B. Boron adsorption with minerals is minimum under low pH however, the adsorption level of B with SOM increases with increasing soil pH (Yermiyahu et al. 1995). The element B association with SOM is more in surface compared to subsurface soils (Tisdale et al. 1985). The bioavailability of chloride does not show any correlation with SOM content (Mortvedt 2000). Among micronutrients cations, Cu binds more tightly with SOM in comparison to other micronutrients and becomes unavailable to plants (Kline and Rust 1966). The Cu deficiency generally appears in the soil having high SOM content due to Cu complexation into insoluble forms (Moraghan and Mascagni 1991). The solubility of Cu in soil decreases complexation with clay–humus particles (Stevenson and Fitch 1981, Sharma and Kanwar 2009) due to highly stable complexes. Complexation of Cu with OM generally occurs in soils having soil pH above 6.5 (Barber 1995).

5.8.3 Soil Redox Potential

Oxidation–reduction reactions occur due to transfer of electron from a donor to an acceptor. Redox reactions are common in Fe (Fe^{2+} and Fe^{3+}), Mn (Mn^{2+} and Mn^{4+}) and Cu (Cu^{+} and Cu^{2+}) (Lindsay 1979). The redox reactions are considerably more important in Fe and Mn than Cu due to higher concentrations in soil. The organic metabolites produced by roots and microorganisms influence the redox reactions in the soil. The redox reactions also affect the availability of nutrients of soils, because the available forms of nutrients to plants are Mn^{2+}, Fe^{2+}, and Cu^{2+}, respectively. The soil pH also influences the redox reactions because more pH favors oxidation and less pH favors minerals reduction. The redox potential of Mn is relatively higher as compared to Fe at specific pH values. At soil pH 6.5, the critical redox potential of Fe^{2+} is 100 mV however for Mn^{2+} it is 200 mV in silt loam soil (Patrick and Jugsujinda 1992). Under the flooded conditions the availability of Fe and Mn increases under highly reduced conditions and becomes toxic to plants. High soil temperature reduces Mn oxides (Sparrow and Uren 1987). The Mn toxicity was higher in warm soils than in cooler soils. Increasing soil ph values reduced the Cu availability to plants which might be due to redistribution of Cu from exchangeable and organic fractions to Fe oxide fractions (Shuman 1991). Zinc did not show any influence on low redox conditions, however submergence of soil results in decreased

Zn concentrations in soil solution (Ponnamperuma 1972). The reduced conditions did not have any influence on B concentrations in soils (Ponnamperuma 1972).

5.8.4 Rhizosphere

The rhizosphere is a soil environment immediately adjacent to plant roots and thus significantly affects the availability of micronutrients. The presence of bacteria, fungi, and microorganism secretions in this zone has been observed. Root colonization with arbuscular mycorrhizal fungi reduces plant's risk to toxic effects of micronutrients in acid soils (Clark and Zeto 2000). The non-infecting microorganisms in rhizosphere improved the nutrients availability and mineral nutrition of plants (Marschner 1995). The root exudates induced chemical as well as microbial changes in rhizosphere and affects the availability of micronutrients (Marschner 1991). Rhizosphere acidification improves the availability of micronutrients, even in calcareous soils. Low-molecular-weight exudates released from roots including organic, amino, phenolic acids, and sugars in the rhizosphere mobilize micronutrients and facilitate the roots in acquiring nutrients that are not easily available. The role of root exudates in increasing the soluble Cu concentrations (Nielson 1976) by dissociating the Cu^{2+} from organic ligands before plant uptake has been well documented (Goodman and Linehan 1979). Redox reactions occurring near roots favors the dissociation of Fe^{3+}–chelates and thus improves the available Fe^{3+} (Romheld and Marschner 1986). Acquisition of Mn by rice grown in aerobic soil apparently was influenced by Fe uptake and soil pH (Jugsujinda and Patrick 1977). Increased solubility of MnO_2 by root exudates resulted mainly from organic acids (Uren and Reisenauer 1988).

5.9 Biofortification

Biofortification acts as a food-based strategy to address widespread deficiencies of vitamin A, iron, and zinc which is a major problem in developing countries. Biofortification programs have three main principles:

1. Aims to produce high-yielding profit-oriented crops with their assured adoption to farmers.
2. Biofortified crops must be beneficial for nutritional health.
3. Farmers must adopt and consume the crops to improve their nutritional health.

Biofortification is the process to improve the nutritional quality of food crops through agronomic practices, conventional plant breeding, or modern biotechnology. Biofortification of crops is the easiest way to improve the nutrient content in populations against the supplementation and conventional fortification in crops. Biofortification continues to receive widespread attention for helping to reduce micronutrient malnutrition in the rural areas of the developing world. Genetic engineering to develop food crops enriched vitamins (e.g., vitamins E, A, riboflavin, and folic acid) and Fe and Zn (Waters and Sankaran 2011; White and Broadley 2009). High-Fe biofortified rice was efficacious in improving the Fe status of women in the Philippines (Beard et al. 2007). Agronomic biofortification is an effective, feasible, and sustainable approach to alleviate micronutrient deficiencies as compare to genetic biofortification, food fortification, supplementation, and dietary diversification. It is considered a short-term solution to increase micronutrient availability. Transgenic/biotechnological approach involves the synthesis of transgenes for nutrient re-translocation between tissues to enhance their bioavailability. Various crop varieties have been biofortified with micronutrient using transgenic approach. To improve Fe and Zn content in the crops, the major emphasis is to increase the uptake and utilization efficiency of plants through variation in transporters expression and suppressing the anti-nutrient (like phytic acid) concentration. Genetically modified rice containing soybean ferritin genes and nicotiana amine synthase resulted in sixfold higher endosperm Fe concentration retaining grain yield and quality parameters (Trijatmiko et al. 2016). The transgenic rice crop with a combination of genes AtIRT1, AtNAS1, and PvFERRITIN (PvFER) resulted in increased grain iron concentration (Boonyaves et al. 2017). The results suggested the Fe accumulation in the vegetative tissues owing to the lack of extra sink capacity in the seeds on sole application of IRT1. In case of vitamins, the adequate regulation of limiting step in the biochemical pathway of seed for the facile production of vitamin A precursor, i.e., β-carotene or alternative pathway for amplified production are the widely accepted transgenic approaches.

The improvement in micronutrient uptake by plant roots can be done by increasing the content of available micronutrients, and more absorption increased in the root–soil interface. Bioavailability of nutrient is the amount potentially available for absorption by plant and utilized for plant metabolic processes. The plasma membrane of root-cell and absorption mechanisms should be sufficient and specific to allow the accumulation of micronutrient metals from the rhizosphere. In seeds and grains, phloem sap loading, translocation, and unloading rates within reproductive organs are important characteristics that must be considered in increasing micronutrient metal accumulation in edible portions of seeds and grains (Welch 1986). The seedling vigor and viability increase with the micronutrient concentration in seeds due to the enhancement in performance of seedlings when seeds are planted in micronutrient-poor soils. In micronutrient-deficient conditions, improved seed favors for the production of longer and a greater number of roots to scavenge more micronutrients and water early in growth (Welch 1999).

Multiple processes, including nutrient acquisition, translocation, and utilization, contribute to overall nutrient efficiency. Each of these is complex process with multigenic origins. Engineering crop nutrient efficiency and maintaining nutrient quality require a multidisciplinary approach involving plant breeding and biotechnology. To determine the inherent potential of crop plants and to improve their nutrient efficiency genetically modified crops are contributing to modern agriculture (Tian et al. 2012). However, using biotechnology and molecular breeding approaches to improve nutrient efficiency little progress has been made.

Biofortification is an innovative technology to address micronutrient malnutrition in a sustainable way. Various approaches including agronomic, conventional breeding, and genetic engineering are used to increase nutrient contents of key nutrients in main food crops (Bouis et al. 2011). It is possible only with collaborations with interdisciplinary scientific institutions and agencies in various regions for the production of biofortified crops with enriched vitamin, Fe, and/or Zn.

5.10 Concluding Remarks

The micronutrient deficiencies have been a serious issue for sustainable agriculture under intensive cropping in recent years due to high nutrients demand, nutrients leaching, loss of top soil, liming of acid soils, unavailability of farmyard manure, impurities in fertilizers, and use of marginal lands in agriculture. Micronutrients availability in soils are affected by several factors, i.e., soil pH, SOM, redox potential, soil biological activity, and clay contents. The plant roots induced changes in rhizosphere region and root exudates to mobilize mineral nutrients from immobile to available forms. The plant root exudates increase the availability of nutrients and also produce water-soluble metal chelates. Micronutrients are similarly important to macronutrients in crop production. The rate of micronutrient application in the soil is from 0.2 to 100 kg ha^{-1}range and it depends on the availability in soil, requirement of particular crops, and application mode.

The requirement of the micronutrients is very low and generally applied in combination with macronutrient fertilizers in the soil. The rate of micronutrients in the soil is higher than a foliar application of micronutrients. There is a need to develop micronutrient-efficient genotypes for the improvement of crop production in the future. The additional information about the micronutrient recommendations needs to be strengthened regarding the availability of micronutrients in soils on short- and long-term basis, effect of micronutrients on crops, availability, the critical deficiency and toxic levels of micronutrients in soils, and plants as well as micronutrients interactions with other minerals in soil and plant systems. Micronutrient deficiencies in soils and plants result in malnutrition in human beings in terms of human health as well as the health economies of countries. Biofortification, a promising strategy to increase micronutrients content in crops, is needed to accelerate development of biofortified foods. In the future, farming community and policy makers of health, nutrition, and agricultural sectors need to work in close linkages to meet the nutrition and health goals of the country against malnutrition.

Kinds of interactions, synergism, and antagonism were observed between the nutrients. When two or more elements improved physiological state of the plant, it is called physiological synergism and when an excess of one nutrient reduced the uptake of another nutrient, it is called physiological antagonism. Optimal levels of Cu and B improve N uptake by the plant. Optimal levels of Mo improve utilization of N as well as increases uptake of P. Optimal levels of Ca and Zn improve uptake of P and K. Inversely, excessive amounts of N reduce the uptake of P, K, Fe, and almost all secondary and micronutrients like Ca and Mg, Fe, Mn, Zn, and Cu. Excess uptake of Fe, Mn, Zn, and Cu. Excess Ca reduces uptake of Fe. Excessive Fe reduces Zn uptake. Excessive Zn reduces Mn uptake. Thus, the interrelationships between nutrients in the plant system are complex and interdependent.

5.11 Ways Forward

Improvement in nutrient use efficiency with the application of existing technologies without affecting environmental quality to improve the soil–crop systems management needs to be explored. The emphasis should be given on screening and development of micronutrient-deficient-tolerant crops and genotypes. The characterization of the adaptation of genotypes to micronutrient-deficient soils should be compared with average cultivars. The production of biofortified food has the dual advantage to provide nutrients to large population without changes in patterns of food consumption. The multidisciplinary approaches including soil scientists, agronomists, plant breeders, farming community, policy makers, and environmentalists are required to work together to deal with the issue of malnutrition and human health. Various safety, technological, and cost aspects should be taken into consideration for proper food fortification programme to provide nutritive food to the population.

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Advances in Input Management for Food and Environmental Security

6

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Abstract

Achieving food security while protecting the environment in the context of future global climate changes is a great challenge to the sustainability of modern agricultural systems. Food production is likely to maintain priority over

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environmental protection. In modern agriculture, input management is very crucial for sustaining future food security and environmental protection which might be achieved by the integration of land, pest, disease, nutrient, and other resource management practices. This chapter focuses on the potential of next-generation input management techniques for safer food production and environmental protection. The possible impacts of next-generation input management techniques for safer and nutritious food production without environmental degradation as along with other vital dimensions of food security have been discussed. Additionally, next-generation input assessment studies, possible integration of

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different techniques, and approaches for food and environment security have been objectively described.

Keywords

Food · Environment · Agricultural input · Frontier technology · climate change

Abbreviations

FAO	Food and Agriculture Organization
FUE	Fertilizer use efficiency
GHGs	Greenhouse gases
CH_4	Methane
N	Nitrogen

6.1 Introduction

Globally, swiftly expanding human population, pollution (water, air, and soil), climate change, decreasing soil fertility, biotic and abiotic stresses, urbanization, and other socioeconomic issues are likely to pose serious challenges (Misselhorn et al. 2012; Poppy et al. 2014; Raza et al. 2019; Brevik et al. 2020; Iqbal 2020). Targeted efforts are needed to ensure food security which entails the provision of safe, sufficient, and nourishing foods all the time at affordable prices (FAO 1996; Bilali et al. 2018). Besides, environmental security is also equally important achieved through restoration, compliance, protection, prevention, and implementation of environmental security techniques (Thomas 1997; Iqbal and Iqbal 2015; UNEP 2019; Islam and Kieu 2020). However, interlinks between food security consequences and environment (ecosystem services) are complicated and multidimensional, because food security is dependent on agricultural inputs and a major driver for the loss of ecosystem services (Ericksen 2008; Kumar et al. 2018a, b). Quality seed, soil, fertilizer, insecticide, pesticides, and water are crucial inputs for crop production. Their excess and inefficient use in the recent past have led to environmental and ecosystem degradation. Therefore, researchers are focusing to develop eco-friendly, sustainable, and more efficient strategies to combat environmental degradation and boost production along with the quality of food (Scialabba and Hattam 2002; Gebbers and Adamchuk 2010; Clark and Tilman 2017; Debaeke et al. 2017; FAO 2017; Das et al. 2018). To achieve these objectives, next-generation input management techniques hold potential as a promising approach to ensure food and environmental security under changing climate scenarios (Ejeta 2009; Lal 2013; Jones et al. 2017; Pachapur et al. 2020).

Accessibility of super quality planting materials including seeds is a fundamental requirement for sustaining future food security under a fluctuating environment and can be achieved by the next-generation approaches (Ayieko and Tschirley 2006; Spielman and Kennedy 2016). In this context, advancement in genetic and molecular breeding approaches (marker-assisted selection, next-generation sequencing, and transgenes) have primed to the progress of boosting harvest (hybrids, transgenics), stress and disease-tolerant, and bio-fortified (rich in quality traits) varieties with higher potential even under different environmental conditions (Varshney et al. 2009; Chikara et al. 2014). Likewise, seed treatments with bio-stimulants, pesticides, insecticides, and the use of synthetic seeds not only protect the emerging seed from different diseases, insects, and soil-borne pathogens but also reduce the load of chemical fertilizers (Rouphael and Colla 2018; Kumar et al. 2020).

The second most important input in agriculture is soil, which provides support, essential nutrients, and water for crop growth. Intensive farming has caused land degradation, soil toxicity, loss of soil fertility, and productivity (Lal 2001; Kopittke et al. 2019, 2020). Therefore, next-generation strategies, such as smart soil, bio-concrete, organic chemicals, and nanoparticles might enhance soil fertility and reduce synthetic substances capacity of the soil (Iqbal et al. 2015a; Panpatte et al. 2016; Paustian et al. 2016; Seifan et al. 2016). Besides, quality planting material and soil characteristics, water is one of the most important inputs for crop production. Its accelerated anthropogenic and extensive use causes water pollution and water crisis for agriculture. For time being, next-generation technologies have focused on water management through digital metering technologies, land management, crop diversification, irrigation scheduling, and drip irrigation (Belder et al. 2007; Bautista-Capetillo et al. 2018; Nikolaou et al. 2020; Nguyen et al. 2020) leading to water conservation (de Vries et al. 2003; Bai et al. 2017; Hatfield and Dold 2019). Moreover, recent molecular and physiological advances for improving crops roots structure architecture, length, weight, density, and hydraulic conductivity for efficient water uptake and transport (Parry and Hawkesford 2010; Fang et al. 2019; Mohammed et al. 2019; Reddy et al. 2019; Falk et al. 2020; Klein et al. 2020).

The application of chemical fertilizer, such as insecticide, herbicide, and systemic poisonous insecticides are major problems of modern agriculture and adversely affect food quality and environmental sustainability (Umesha et al. 2018; Zhang et al. 2018; Elahi et al. 2019). However, in recent past, the application of biopesticide, insecticide, herbicide, and bio and nano-fertilizer mostly in developed countries has led to organic agriculture and improved food production without loss of ecosystem services (Scialabba and Hattam 2002; Iqbal et al. 2015b; Durán-Lara et al. 2020).

Considering the above facts, this chapter reviews the potential of next-generation input management techniques for food and environmental security. In addition, emphasis has been placed on the next-generation multidimensional input assessment studies and the possible integration of different techniques and approaches for food and environmental security.

6.2 Next-Generation Input Management Technologies: Concepts and Prospects

Green revolution entailing improved crop varieties and utilization of synthetic fertilizers and pesticides significantly bolstered crops yield (Iqbal 2018; Iqbal et al. 2019; Khaliq et al. 2019; Siddiqui et al. 2019; Faisal et al. 2020). The strong interconnection between farm inputs and crops improved the food and nutritional security, while modern next-generation methodologies aim to minimize the loss of farm inputs. However, for the last decade, the grain yield of most of the staple crops has become stagnant while decreasing land area under cultivation, and increasing human population are putting pressure on agricultural resources (Shamshiri et al. 2018; Kumar et al. 2021). Besides, substantial losses of nutrients and pesticides from agricultural fields have become major sources of environmental pollution, which are threatening the sustainability of cropping and other agroecological systems. This scenario demands another green revolution, especially with respect to environmental fluctuations globally. The handling of next-generation input methodologies holds a promising tool to boost agricultural productivity through the effective utilization of input resources. The concept of next-generation input management technology encompasses effective management of farm inputs through a combination of advanced mathematics for inputs (fertilizer, pesticides, seeds, irrigation, etc.), for per unit area, automation, sensor systems advancements, and next-generation plant breeding. These technologies integrate science and technology to work in cohesion for delivering a step change in crop yields and growing more produces from lesser inputs (Posadas 2012; Saiz-Rubio and Rovira-Más 2020; Talaviya et al. 2020).

These technologies are setting the stage for another green revolution, directing possible means of viable and guaranteed farming in future under the context of the world facing drastic environmental changes, along with paving the way for securing healthy dietary needs of masses across the globe. Closed ecological systems having no reliance on matter exchange from outside the system have the potential to clean atmospheric air by converting unwanted goods into oxygen, organic manures, and irrigation for ecosystems. Currently, the availability of particular arrangements is only in minor scales because of the limited technologies that hamper the scaling. Automated farm groups involving theoretical groups of agricultural automated systems with thousands of minute devices grow crop plants, supply inputs, monitor crop growth, and soil health predict crop yield, with practically no human intervention. Similarly, vertical farming, encompassing crops cultivation within enclosed or multipurpose towers reduce transportation costs of farm inputs along with the provision of quality food. Moreover, nano-based fertilizers and pesticides were introduced (DeRosa et al. 2010; Adisa et al. 2019; Shebl et al. 2019; Usman et al. 2020), having the possibility of penetrating plant roots more efficiently, and thus their loss to lower horizons as well to the environment as gaseous emissions decline significantly compared to bulk chemical fertilizers and pesticides (Zhang et al. 2006; Mikkelsen 2018; Iqbal 2019).

6.2.1 Perspective Mathematics Revolution for Input Management

For the effective management of agricultural farm input resources, advanced mathematical processes involving the latest generation of computing, software, and hardware hold promise for boosting farm productivity (Posadas 2012). For instance, simulation models utilizing historical data enable farmers to determine the optimal sowing time, fertilizer requirement, etc., based on reliable information. Effective crop input management can never be achieved without using high-yielding varieties, while advanced mathematics has enabled plant breeders to identify crop varieties having higher yields along with desirable traits, such as insect-pest resistance and inherent ability to tolerate environmental stresses including temperature extremes, water scarcity, salt stress, heavy metals toxicity, etc. Besides, the mathematical revolution can potentially assist in scheduling farming activities from the harvest to loading trucks in such a manner that ensures delivery of fresh crops to the market (Shamshiri et al. 2018; Meena et al. 2020). Last but not least, the mathematics revolution imparts power to the entire agricultural supply chain to make informed decisions about using input resources leading to higher utilization efficiency and multiplied grain yields. However, the perspective mathematics revolution has a limitation that high-quality data are needed to be fed to the simulation models, miscalculations might lead to reduced utilization efficacy of farm inputs.

6.2.2 Perspective Sensing Revolution for Input Management

Advanced sensor technologies enable a real-time estimation of input requirements on modern farms. The latest equipment utilizes smart sensor networks that actively monitor soil health along with the water and nitrogen needs of crop plants. In this way, precise data on soil fertility status and moisture content helps to apply irrigation and fertilizers optimally, leading to scarce resources conservation and yield maximization (Panchard et al. 2014; Paek et al. 2014; Stevanato et al. 2019; Burton et al. 2020; Erler et al. 2020; Ferrarezi et al. 2020). In addition, sensors help real-time traceability of applied nutrients and the diagnosis of crops along with determining the status of farm machines (Rai et al. 2012; Saiz-Rubio and Rovira-Más 2020). Thus, the perspective sensing revolution holds the promise to optimize the use of water and chemical fertilizers that are vital for leading to environmental protection. The promising use of nanotechnology and its products in next-generation agriculture and environmental sustainability is highlighted in Fig. 6.1. Besides, various high-resolution crop sensors, direct use of equipments (sprayers, seed, and fertilizer drills, water drips, etc.) to supply the needed amounts instead of prescribing fertilization before application (Wen et al. 2019; Yadav et al. 2020).

Optical sensors or drones can identify crop health using infrared light across the field. Along with the management of farm inputs, animal collars having integrated biometric sensors and Global Positioning System (GPS) furnishes real-time monitoring regarding the actual location of animals and thus enabling ranchers to respond quickly in case of any emergency. Precision agriculture, which is intra-field

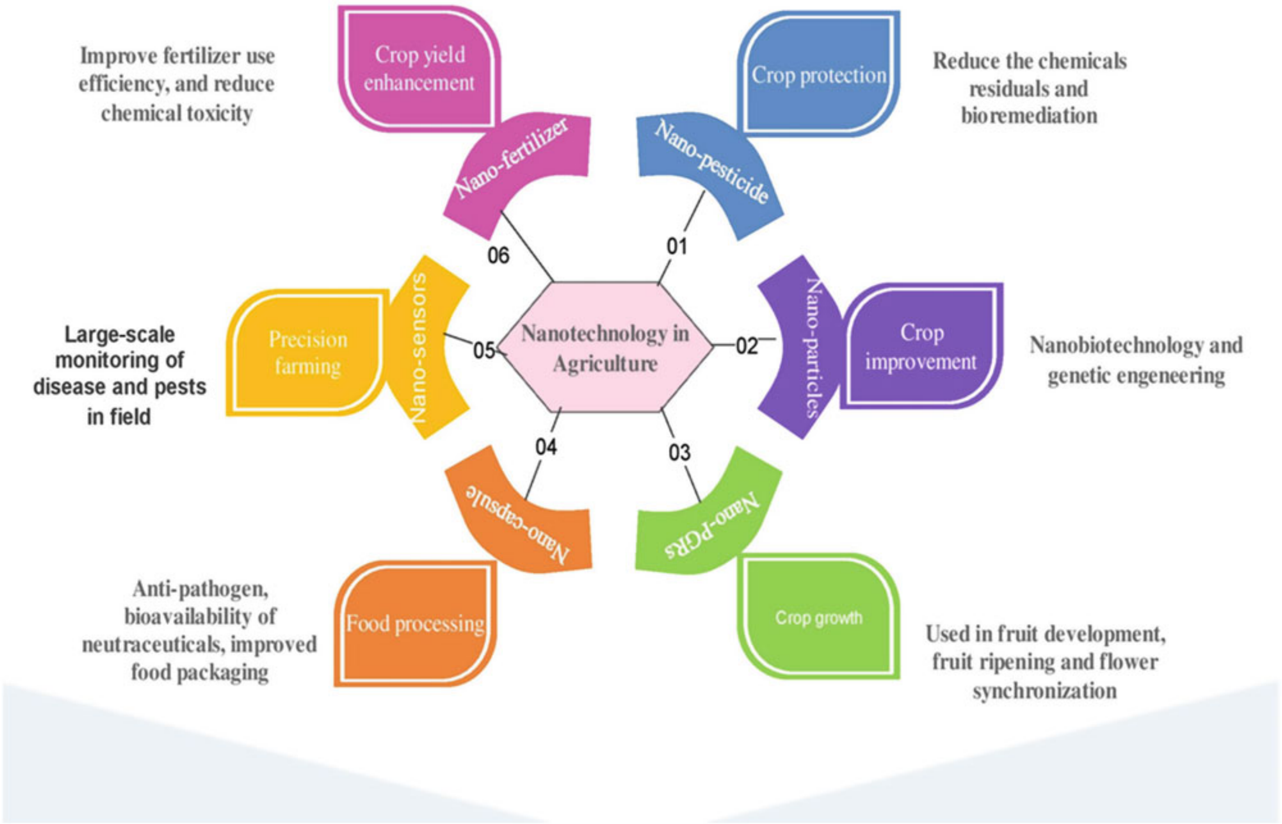

Fig. 6.1 Highlights the implication of nanotechnology and its products in next-generation agricultural improvements

variations observation-based farming management, can also be assisted by high-resolution sensors leading to sustainable farming (Barkunan et al. 2019; Müller et al. 2019; Kayad et al. 2019; Mulley et al. 2020). These technologies can multiply returns on inputs used by preserving scarce resources at ever-larger scales. Furthermore, the use of precise sensors with crop variability information and geolocated weather data allows accurate and improved inputs use (Shamshiri et al. 2018). Thus, the perspective sensing revolution not only has the potential not only to optimize nonfarm inputs but also monitoring choices for actual conditions of crops and animal location in grasslands.

6.3 Perspective Automation Technology for Input Management

Engineering encompasses cutting-edge technologies that boost the level of farm input management to new means (Tillett 1993). Of particular, interest will be the development of smart devices that have the potential to perform input supplying operations independently as per programmed data without human intervention. The use of artificial intelligence, such as robotics (for sowing, picking fruits, and chemical spraying), drone (handling agriculture operations at large scale), satellite (for prediction of weather), digital application (for giving timely information), and advanced molecular strategies in next-generation agriculture are highlighted in Fig. 6.2.

Automation integration with high-resolution sensing and advanced mathematics ensures optimization of planting time, irrigation needs along with other input applications with absolute precision. Agricultural robots (also known as agbots)

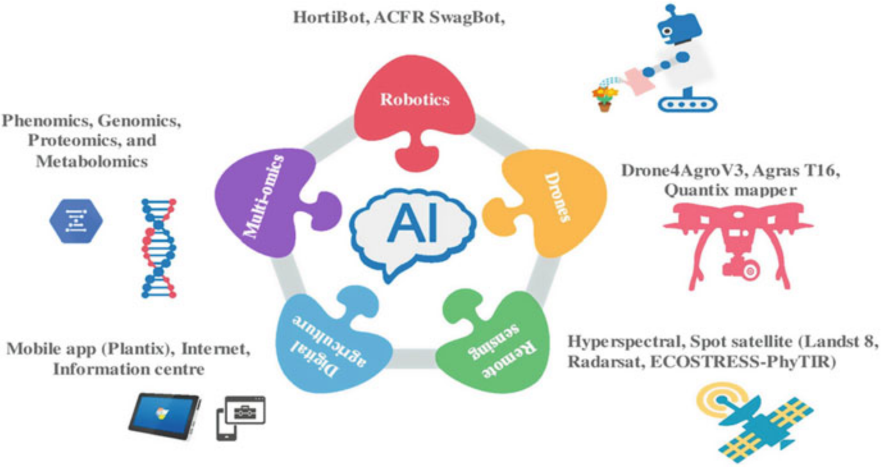

Fig. 6.2 Highlights of some of the automated machines (Artificial Intelligence (AI)) in the next-generation agriculture

have been designed and manufactured to perform numerous automated agricultural tasks that are quite tedious, such as weeding, spraying, fruit picking, etc. (Tarannum et al. 2015). The perspective is the utilization of energy-efficient robots which are designed to work in a network for monitoring actual conditions of agricultural fields and subsequently supply essential inputs without human intervention. Moreover, automation is bound to help sustainable farming via micro and large-scale robotics to check and thereafter maintain crops at the plant level. Thus, using robots for crop input management means fewer farm injuries and less environmental pollution owing to insignificant and negligible waste of synthetic fertilizers and pesticides, especially of higher shelf life. Moreover, variable-rate swath control is another critical advantage associated with the use of robotics in managing farm inputs. Future swath control technology using geolocation tools has the potential to substantially save seeds, minerals, fertilizers, and herbicides by avoiding overlapping of applied inputs. This technique involves precomputing the field shape and clearly understanding the relative productivity of different areas; equipment or robots can procedurally supply inputs at variable rates throughout the field, which leads to input saving along with higher utilization efficiency (Tillett 1993). However, the limitations are the expensiveness of robotic uses, the occurrence of technical glitches, and high-tech operation and maintenance, which necessitates further refinement of agricultural robotics technology for the effective management of farm inputs. Equipment telematics is another next-generation farm input management technology that allows mechanical devices, such as boom sprayers, seed-cum-fertilizer drills, and tractors to warn out about faulty operation.

6.4 Next-Generation Plant Breeding to Increase the Utilization Efficiency of Farm Inputs

Keeping in view the increasing population, boosting agricultural productivity with meager use of farm-applied resources has become a necessity. In the years ahead, the global population has been projected to increase by two billion, and their dietary accessibility can only be guaranteed through boosting crop yields via effective handling of farm inputs. Moreover, due attention needs to be given to environmental pollution and degrading biodiversity owing to excessive loss of farm inputs from agriculture fields. The overall efficiency of farm inputs needs to be much higher securing uncertainties that agriculture is facing during changing climate and global warming. The necessity of breeding cultivars having higher inherited potential to utilize inputs and produce higher biomass as well as economic yield has become the need of time (Barabaschi et al. 2016). Thus, to improve the utilization efficacy of farm inputs, one of the most exciting advances could be the development of crop hybrids having the potential to utilize higher amounts of applied inputs (by modified roots architecture, botanical superiority, and adaptability) and which thrive well in ultrahigh densities under environmental stresses including temperature extremes, water scarcity, salt stress, ion toxicity and water-logging. The next-generation selective breeding encompasses a quantitative analysis of end results while suggesting improvements algorithmically (Harfouche et al. 2019). Artificial intelligence assisted plant breeding for desired traits enabling crops to utilize inputs (fertilizers and water) with greater efficacy leading to boost crop yield, thus safeguarding food and nutritional safety of masses across the globe. Therefore, next-generation plant breeding holds a promising perspective to bolster water and fertilizer use efficiency leading to higher crop yield. The key next-generation approaches in environmental safety are summarized in Table 6.1.

6.5 Dietary and Ecological Safety Through Novel Technology: Filling the Gap Add a Flow Chart

By 2050, the global population will be nearly 10 billion which is bound to double the food insecure population (Poppy et al. 2014; Ranganathan et al. 2018; Islam et al. 2020; Hossain et al. 2020). Therefore, the global agricultural system needs to be drastically transformed to produce sufficient food for its increased population to ensure food security (FAO 2017).

Two major challenges of current and future agriculture are uplifting crop productivity with minimal inputs while implementing measures to minimize undesirable ecological events (Beddington 2009). Global ecological events affect negatively crop growth and predict more climatic events exacerbating crop growth triggering heat, precipitation, and weather events (FAO 2016a, b). The major agricultural resource, such as water and labor are diminishing, and besides, the fertility level of the cultivated land is also decreasing (FAO 2016a, b; Kanianska 2016). Cater to the global food requirement for the growing life on earth, intensification of crop growth, as well as the applying agrochemicals including chemical fertilizer and pesticide, are increasing tremendously, which negatively impacts the ecosystems and living beings (Kumar et al. 2019). Current farming practices that are more resource-intensive and responsible for major Greenhouse Gases (GHGs) emissions are no longer sustainable. Therefore, exploring novel concepts of research concurrently focusing on boosted crop production, while minimizing ecological consequences are a prime objective for catering future food demand (Godfray and Garnett 2014). The general term, “sustainable intensification” explains the enhancement of agricultural productivity in prevailing lands under agriculture by increasing the crop and livestock productivity and profitability, food security and health of human, social and gender equity, and environmental impact on biodiversity (Kehoe et al. 2017; Cassman and Grassini 2020). Sustainable intensification is likely to target-related than the other approaches, highlighting the significance of environmentally friendly agriculture production systems with minimal carbon footprints (Evans 2009; FAO 2011a).

Provisions of food and nutrition to all livelihoods on earth are defined as food security (Venugopal 1999). The interactions of agricultural production systems and external environment are quite complicated networking systems thus, efficient and smooth handling and integration of related activities are paramount for a better outcome (Ericksen 2008). Thus, boosting agricultural production system while balancing environmental impacts through minimal carbon footprint, giving

Table 6.1 Summary of key next generation approaches, strategies, and their application in the environment safety

S. No.	Next-generation approaches	Strategies	Application	References
1	Nanotechnology	Implementation of NPs-based smart input system (seed treatments with micronutrients; nano-fertilizers (nano N, P, K), nano-pesticides, nano-insecticides, and nano-capsules)	Plant disease, insect resistance, efficient nutrient utilization, improve fertilizer use efficiency, abiotic stress tolerance, and reduce the chemical load on soil	Panpatte et al. (2016), Duhan et al. (2017), Shang et al. (2019), Moulick et al. (2020)
2.	Artificial intelligence	Artificial intelligence (AI) makes it possible for machines to learn from experience, adjust to new inputs, and perform human-like tasks	It helps in yield healthier crops, control pests, and diseases, input resource managements, decision-making, and improve a wide range of agriculture-related tasks in the entire food supply chain	Nabavi-Pelesaraei et al. (2016), Sánchez et al. (2020), Talaviya et al. (2020)
3.	Advanced molecular breeding	Genome editing, transgenics, multi-omics (genomics, metabolomics), and next-generation sequencing	Introduction of desirable traits (biotic and abiotic stress tolerance, improve multiple input use efficiencies (water, light, and nutrient)	Reddy et al. (2020), Singhal et al. (2021), EL Sabagh et al. (2021), Kumari et al. (2021), Indu et al. (2021)
4.	Improved agronomical practices	Precision farming, automated irrigation, climate-smart agriculture, conservation agriculture and crop models, zero tillage, crop residual management, cropping pattern	Improve the input use efficiency, more production and productivity, and higher benefit/ cost ratio	Branca et al. (2011), Nyagumbo et al. (2017)
5.	Improved soil and water management	Growing cover crop, organic manure, application of biochar, soil nutrient analysis, irrigation scheduling	Improve soil nutritional status, fertility, improve water holding and utilization efficiency, and reduces the	Hoorman (2009), Jatav et al. (2020)

(continued)

Table 6.1 (continued)

S. No.	Next-generation approaches	Strategies	Application	References
			chemical load on soil	
6.	Conservation and restoration of ecosystem	Zero tillage, less mechanization in the field, restricted human interference in the natural ecosystem, adopt green technology, grow more trees, and sustainable natural resource management	Improve environmental sustainability, reduce soil and environment pollutions, nullifying the effects of climate change, and maintain natural biodiversity	Young (2000)
7.	Reduce GHSs production	Modified rice cultivation practices, reduce fertilizer applications, and restricted the burning of agricultural bi-products	Reduce the global warming effect on crop production	Smith et al. (2007)
8.	Reducing pre and postharvest losses of food	Improved agricultural practices, timely harvesting, development of warehouse facilities, strengthen the market facilities	To fulfill the future global food security	Prusky (2011)

provisions to food for all, protecting natural ecosystems, improving crop yields by various breeding tools, utilizing species diversity, genetic improvements of crop and animal by modern techniques, and harnessing trade and e-commerce are required to achieve food and environment security (Beddington 2010; Tomlinson 2013; Godfray and Garnett 2014). To achieve food and environmental safety for the increasing population, the following approaches can be implemented are discussed followed and presented in Fig. 6.3.

6.5.1 Improved Crop Breeding Adapting to Environmental Changes

The drastic fluctuations in the environment are projected to adversely affect the whole agriculture production system with over 5% drop by 2050 if adaptive cultivars

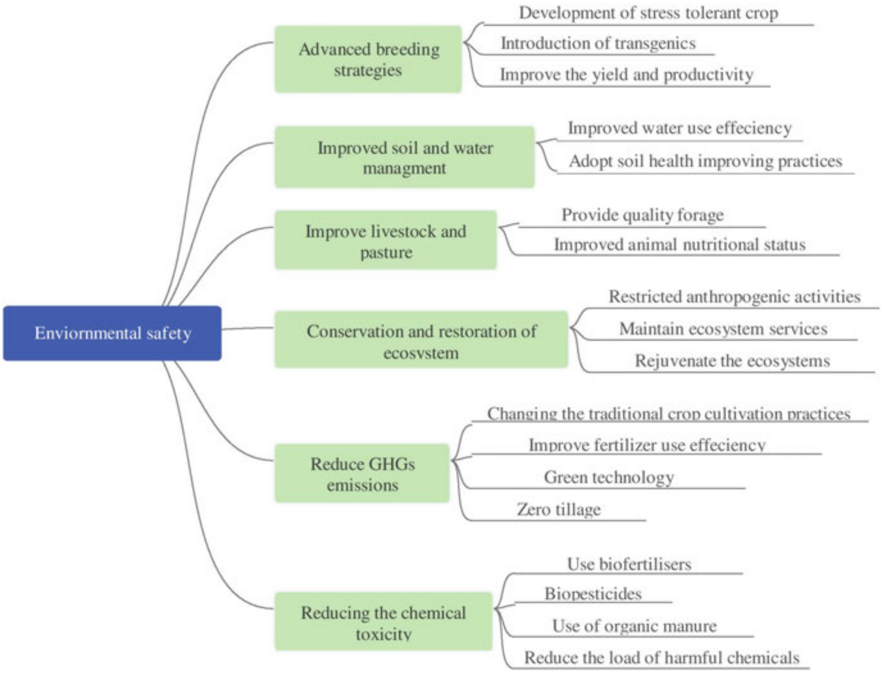

Fig. 6.3 Schematic representation of strategies used for future environmental sustainability

are not developed to boost yield (Ranganathan et al. 2018). Adaptation will require growing alternate crops as well as breeding crops that can cope with changing climate, stresses (biotic and abiotic), and require fewer resources. Advances in molecular breeding and biotechnology offer great potential to increase yield gains by deliberate manipulation of target genes for particular traits, and by editing or slicing genes. Although major crops have received due attention but more efforts are needed to breed minor crops (e.g., millet). The prime aim of new targeted breeding programmes jointly carried through public–private partnerships should be to develop cultivars having better adaptability to climate changes.

6.5.2 Increasing Cropping Intensity

Cultivating prevailing agricultural lands intensively introducing modern cropping techniques would be ideal for enhancing land-use efficiency within the existing land area. Therefore, appropriate cropping systems that will be highly suitable in a particular area and will increase the system productivity need to be identified. Increasing annual cropping intensity by 5% beyond 2050 is said to be reduced land requirement by 14% and the GHGs modification gap by 6% (Ranganathan et al. 2018). Future research needs to be directed toward designing such intensive cropping systems relevant to the availability of inputs and considering other limitations.

6.5.3 Improved Soil and Water Management

Using novel practices for soil and water management, cultivation of damaged lands especially the drylands having less organic matter can be augmented. Agroforestry (incorporating trees with crops) is a great option to recover the damaged lands thereby enhance land productivity. For water scare and salinity areas, rainwater harvest using an artificial pond is an excellent option to improve water management. In the intensive cropping area, green manuring crops (e.g., *Sesbania* spp.) can be cultivated for a short time and then incorporated with the soil, which will increase soil fertility and soil health. In rice cultivation, alternate wetting and drying practices can save a significant irrigation water requirement (Lampayan et al. 2015).

6.5.4 Increase Livestock and Pasture Productivity

In developed countries whereby crop yields have been maximized, there is little scope for further improvement. The potential yield can be easily achieved in animal husbandry by taking care of the wellbeing and health of farm animals (Ranganathan et al. 2018). Progress of knowledge on animal structure and functions, social behavior, etc. are the best indicators to evaluate resilient animal breeds. The demand for products from farm animals is increasing and is estimated to increase by 70% by 2050. Therefore, boosting pasture productivity is a feasible solution to increase food production for animals (Ranganathan et al. 2018). Improving animal nutrition status through the provision of quality forages and other feedstocks might lead to a significant increase in milk and meat productivity as suboptimal nutrition seriously decreases farm animal's productivity and economic returns (Iqbal et al. 2015c). The exploitation of alternate feed sources, such as crops leftovers, weeds, tree leaves, nutritionally improved forage species, etc. might bring another white revolution provided animals feeds are met as per their requirement. Based on the reliable data set, different nutrition models might be developed to determine the nutritional requirements of dairy animals to their physique, growth rate, production potential, and overall health condition.

6.5.5 Reduced Loss and Waste of Food

A huge percentage (33%) of global food produced is lost or wasted throughout the production chain from field to fork. The events and consequences of such losses and wastes are due to poor or inadequate harvesting techniques, storage, and cooling facilities in difficult climatic conditions, infrastructure, packaging and marketing systems, inefficient management, communication gaps among players in the supply chain (FAO 2011b). Thus, significant loss of resources is inevitable. Meantime the by-products such as GHG emissions create extra burden as environmental pollutants exacerbating the situation. In this context, the production chain from field to fork necessary to be reinforced by farmer empowerment through public and private partnerships. The policies related to food supply chains in developing countries need to be restructured while strengthening infrastructure.

6.5.6 Reduced Biofuel Production in Agricultural Lands

The bioenergy production in agricultural lands has negative impacts on global food security expanding the food, land, and GHGs mitigation gaps. Development of bioenergy production in many countries of the American continent and Europe currently facing the drastic rising prices of food and feed including grains, oilseeds, and vegetable oils (Babcock 2015). Therefore, it is urgent to avoid biofuel crop cultivation in food cropland.

6.5.7 Conservation and Restoration of Natural Ecosystems and Restricted Shifting Cultivation

The improvement of agronomic practices is key to protect global green biomes by limiting the transformation of natural habitats into agricultural lands. In certain situations, unfertile bare or marginal lands could be converted to natural forests through restoration (Ranganathan et al. 2018). In addition, agricultural practices need to be transformed into a more sustainable manner to avoid further damaging of an ecosystem, while restoration and conservation plans need to be developed on a priority basis. Furthermore, changing climate and global warming have negatively affected flora and fauna of terrestrial and marine ecosystems which must be assessed by utilizing the latest technologies including global positioning systems and remote sensing (Smartt et al. 2016).

6.5.8 Increase Fish Production

People who live in poverty have limited or less access to nutritionally high diets to safeguard their nutritional requirements and food security (FAO 2011b). The diet of poor people often depends on the cheaper starchy food, such as wheat, maize, or rice, and economically do not strong enough to purchase meat, fruit, and vegetables. Fish is cheaper than meat, and contains higher protein contents, enriched with essential minerals and vitamins, and can provide a more diverse diet for many poorer households. To improve fish productivity, more research and extension work is needed in both freshwater-and marine-based farms.

6.5.9 Reduce GHGs Emissions from Agricultural Production

Agricultural activities have a significant contribution to GHGs emissions, and it is said to be that roughly 26% of all GHGs emissions originate from agriculture production systems (Ritchie 2020). Among agricultural practices, which are mainly responsible for GHGs emissions are rice cultivation, application of nitrogen fertilizers, livestock farming, and energy use. Among agricultural emissions, only the rice sector contributed around 11% of total GHGs emissions (Smartt et al. 2016), in the form of methane. However, there has been a huge scope to reduce GHG emissions in rice production by changing its production practices. For example, in Asian countries, the common rice cultivation method is puddle transplanted rice, which is resource intensive. However, direct-seeded rice has emerged as an alternative rice production technology that has the potential to save water and labor resources as well as lessen methane (CH_4) gas emission by restricting the time period of field flooding (Pathak et al. 2013). Continuous standing water in the rice field is a common practice in Asian counties; however, alternate wetting and drying in the rice field showed lower CH_4 releases up to 90% additionally conserving water and in some cases, it also increases rice yields (Lampayan et al. 2015). Some rice varieties have the potential to generate less CH_4. Therefore, rice breeding programs need to be more emphasized on lower CH_4 rice varieties and less nitrogen (N) requirement, and those which can tolerate more water stress with boosting rice yields (Zhang et al. 2018). Globally, the use of N-fertilizers is tremendously increasing, however, the higher portion of applied fertilizer is lost as gas emissions and leaching. The Fertilizer Use Efficiency (FUE) can be enhanced by improving fertilizer management practices thereby enhancing the nitrogen absorption rate of the crop by genetic modification or crop varieties require less nitrogen or ability to fix nitrogen biologically is urgent (Zhang et al. 2015). Recent advances in the chemical application that avoids converting N into nitrous oxide, and cultivating pastures that regulate this activity naturally are also needed. The sequestering of carbon in soil is one of the mitigation strategies of GHG and therefore, activities to boost carbon retention in soil including zero-tillage farming (conservation agriculture), conversion of forests, and introducing novel approaches for making carbon where soil fertility is essential for food security can be very much useful (Jat et al. 2020).

6.5.10 Reducing Pesticide Risks to Farmers and the Environment

Pesticide use in agriculture has increased and continues to multiply tremendously for increasing food production in intensive commercial-oriented farming systems. Judicious and safe use of pesticides is urgent to minimize the health hazards to farmers and the environment. The use of highly hazardous pesticides needs to be reduced, and a stewardship guideline is required on pesticide use for each country, which will guide farmers to understand pesticide risk and its safe use.

6.5.11 Harnessing Trade and E-Commerce

We are very close to the digital world, and e-commerce has great potential to help bridge the gaps and promote agribusiness. More needed actions to be taken to improve the online marketing of agro-based products.

6.6 Next-Generation Modeling Tools for Sustainable Input Management and Crop Production

Crop modeling in agriculture is a key supportive factor for regulating sustainable agriculture. Different crop simulation models like APSIM (Agricultural Production Systems Simulator), DSSAT (Decision Support System for Agrotechnology Transfer), and DNDC (DeNitrification-DeComposition) (Keating et al. 2003; Holzworth et al. 2015; Jones et al. 2017; Rahman et al. 2018, 2019; Zhao et al. 2019) are working, and provide an estimation of resources to the researchers because of the natural resources become scares under climate change scenarios. To fulfill current and future needs, modification of crop models according to special cropping systems is direly needed. Currently, mostly crop models can work on a crop, but cropping rotations and intercropping schemes also require models for better estimation of resource use efficiencies (Wajid et al. 2014; Awais et al. 2017a, b; Ullah et al. 2019). So, the future crop model's languages, documentation, visualization, and framework should be easy for researchers (Holzworth et al. 2018) and should be included modern farming techniques and analysis features.

Decision-makers of both private and public sectors have engaged agricultural system models as important tools for the prediction and assessment of the capability of the growing systems. The valuation of the need for user-friendly knowledge tools that would help or facilitate the utilization of model outputs was considered a distinguishing feature of the next-generation study. Hence, cloud-based analytical tools and mobile application technology, and other such types of well-defined knowledge-based products can use models more efficiently under a diverse set of stakeholders in comparison to current possible situations. Moreover, there is a need to devise a positive approach that would help in upholding the group of people-related research agenda and agricultural systems modeling in the right direction of next-generation vision (Dokoohaki et al. 2016; Antle et al. 2017; Jones et al. 2017; Tariq et al. 2018; Siad et al. 2019).

6.6.1 Evaluation of Input Uncertainties

Most of the climatic models are considered deterministic unless having uncertain outputs in reality. However, different methods, such as computer-based models, emulation of the model, and sensitivity analysis, have been used for the estimation of uncertainty of deterministic models (Uusitalo et al. 2015). For the assessment of the variance of studied parameters and output of deterministic models, professional expert assessment can also be engaged. More uncertainties in the stakeholders' knowledge and input values' parameters can be quantified by stakeholder opinion, and probabilistic approaches (Van der Lippe et al. 2011). For example, uncertainty for a particular parameter can be estimated through information recorded from the range of variance or quartile of studied values of a particular parameter. Higher inputs of stakeholders might be required when there is higher uncertainty (Sahin et al. 2014). Moreover, higher uncertainty provides supportive extra evidence to enhance assurance in the projected insecurity. According to Morris et al. (2014), free web-based software tools are also available, which help in the elicitation of skilful experiences as probability distributions. Furthermore, the degree of agreement and modeling the disagreement as insecurity can be used for the enhancement of the elicited information (Krueger et al. 2012). The degree of uncertainty has been estimated by Van der Lippe et al. (2011) in the particular data of stakeholders by investigating the degree of gaps between them. Bayesian Decision Network (BDN) approach was used instead of limited system mechanistic models due to very high insecurity (Catenacci and Giupponi 2013). Some uncertainties lead to ambiguities, such as twisting of elicitation outputs owing to a lack of reliable data availability. For the good representation of ambiguities, imprecise probability theory has been proposed by Rinderknecht et al. (2012). Moreover, the bias in the stakeholder elicitation can be present. Similarly, a protocol for the integration of local data with expert knowledge and a Bayesian approach for the assessment of common cognitive biases were proposed by Scholten et al. (2013).

6.6.2 Model Design Criteria for Future Generation

Particular goals distinct from the GB-QUEST govern the plan of the AgFutures model. Therefore, to engage the stakeholders in a debate and to assemble realistic scenarios of the desirable futures, GB-QUEST looks for two potentially opposing goals (Carmichael et al. 2003). As compared to other traditional land-use models, GB-QUEST implies diverse plan criteria for that particular model. Hence, several criteria for the model plan which have been done in the model are given as under:

6.6.2.1 User-Friendly, Simple Interface

The most important object to make a model is to engage society in the context of sustainability. A broader array of problems should be shown and easily displayed in the interface to engage users to make the model more important to a broad person and group's variety. The development of an interface that is user-friendly and easy-to-understand is important for the easy understanding of main constraints, which are shown to the users as questions and their solution to the general public by preventing scientific terms through this interface. Therefore, under the preferred conditions, these answers to questions stated the model components, which ultimately produce future consequences.

6.6.2.2 Involvement of Stakeholders

The authentic issues and viable options that are endured by the society which are of serious concern to the society should be addressed by the models for policy support (Iqbal et al. 2015a). Therefore, the steps involved in the identification of issues that act as the precursor for the model development, engage stakeholders along with policymakers, while the typical approach of stakeholders involves the stakeholders in decision-making of policy that have been preferred and assessed by the model experts solely in the final phase of selection from a particular agreed guideline (Ejeta 2009). Therefore, both of these approaches are in contrast to each other in involving the stakeholders for policy development. In the process of demonstrating the fundamental issues of agriculture and outcomes, an imperative role is played by the stakeholders to make AgFutures more appropriate and satisfactory by the society for its use (Iqbal 2020). Furthermore, to tackle the issues related to the community helps the policymakers. Based on this approach, policies formulated were socially acceptable by the community.

6.6.2.3 Integrated Approach

Integration of both physical and social sciences can potentially evaluate complex land-use systems and related sustainability analysis. The integrated models provide less information regarding important issues but are easy to use and implement. Whereas, the disciplinary models provide more information about important issues, but their application is complex. However, the utilization of a systematic approach of integration of the disciplines, resolutions, styles, and degrees of certainty is the main objective of integrated modeling (CIESIN 1995). Models of land use with curative nature are presenting in different proportions, biotic or abiotic related to land-use change and presenting just one proportion of land-use change systems due to more complexity (Veldkamp 2001). At multiple scales, integration of human and natural proportions of land-use systems might evaluate their effects on economic, social, and environmental sustainability on well-defined sustainability indicators for the assessment of balanced perception, the integration of three components of sustainability variables is required to emphasize in comparison to those analyses that highlight just environmental or economic impacts of the particular system in AgFutures higher.

6.6.2.4 Complexity, Quick, and Invisible Back-End Model

When AgFutures is integrated with GB-QUEST, then there is a need for the assistance of a back-end model which is designed in such a way that the actual modeler rule implements with the experience to produce the anticipated consequences for users, while just the very last-related outputs are shown. Moreover, the underlying model provides issues and outputs widely, which is generally established on a complicated web of related connections that only describes the viable options and outputs. Furthermore, it utilizes the complicated technology for the production of ‘what-if’ scenarios concerning land-use changes and the estimation of associated impacts on community, economy, and ecological outputs. Larger time has been spent on designing a model, such as statistical formulae, assessments regarding significances used for appropriateness of land, and coefficient of models aimed at reducing the setting period for run-time calculations, which in turn help in permitting the rapid generation of future scenarios. Moreover, the choices of a user vary the value of main variables allowing the quick production of 'desired' scenarios.

6.6.2.5 Scenarios-Based Approach

Generally, predictive models emphasize forecasting the future based on past history. However, predictive models are unsuccessful in identifying particular future scenarios arising from actual and anticipated future choices. The application of that scenario associated with backcasting strategy should be used for decision and policy making rather than keeping the future predictable, and it presents that our community has substantial control over the future consequences (Sharma et al. 2006). Moreover, the model uses the scenarios-based strategy, which allows users to evaluate various assumptions regarding the values and behavior of humans and technology and institutions, but these assumptions are rarely applied in predictive models.

6.6.2.6 Tackle the Uncertainty

When climatic models are engaged for the estimation of unusual futures, then there is a need to evaluate the uncertainty adjacent to the system's behavior in a user-friendly way. Hence, the necessity of evaluating the risk factors is particularly related to situation of the generation of a model having uncertainties from several kinds of actions and that hope to think schedule distant into the particular future. Strategy based on the scenarios---applied consists of the unambiguous capability to observe how scenario changes under various presumptions concerning the particular aspects of uncertainty, comprising the values and behavior of humans and technology and institutions. The application of scenarios also gives resources to check the sensitivity of variables, i.e., prices (Sharma et al. 2006).

6.7 Next-Generation Input Management Technologies for Food and Environmental Security

Attaining food security in a seamless squall is a key contest for society. If by 2030, 50% of food, 50% of energy, and 30% of freshwater cannot be used, then the "perfect storm" will appear on a global scale at the same time, which will be a "storm" (Beddington 2009). When temperature change and a growing world population act along, this will become an even more "evil problem," which makes the challenge of achieving world food security a lot of advanced and severe. Food security "exists when all people have biophysical and economic access to adequate, safe and nourishing food at all times to feed their nutritional needs and dietetic partialities for an active and healthy life" (FAO 1996; Beddington 2009). This is dictated by four elements: (1) accessibility (from rural creation and land use or trade); (2) strength of gracefully (e.g., occasionally and from year to year); (3) access (relies upon monetary assets yet in addition on physical access and social elements);

and (4) organic utilization of food (for e.g., dietary assorted variety and sanitation issues) (Barret 2010). It has been assessed that about one billion individuals experience the harsh effects of hunger because of the absence of macronutrients (FAO 2010), and one billion individuals lack adequate micronutrients, which is unsafe for wellbeing or improvement. (Foresight 2011).

6.7.1 Food Security

Ensuring adequate, safe, and nutritious food for all people has been a major global challenge truly in the twenty-first century. Food security is typically characterized in four measurements: food accessibility, admittance to food, food use, and food strength (FAO 2016a, b). These aspects form a common basis for the definition established by the Food and Agriculture Organization of the United Nations (FAO): "Food security exists when all individuals, consistently, have physical, social and financial admittance to adequate amounts of sheltered and nutritious food, which meets their dietary needs and food inclinations for a functioning and solid life" (FAO 2016a, b). For every aspect, a progression of pointers has been characterized to survey progress in improving food security.

6.7.2 Input Management Technologies for Environmental Security

The concept of sustainable intensification covers a significant number of the subjects in this extraordinary issue from an overall perspective, yet, there is still no agreement on its viable application (Garnett et al. 2013). Given that numerous archives in this issue have communicated the need to consider crop needs while ensuring human wellbeing and nature, everybody approves those ideas like sustainable intensification can advance powerful arrangements and works on during the change of horticultural frameworks. Consequently, it is recognized as a worldwide need. The success of this concept needs to be wide enough to cover sophisticated intensive farming systems in developed countries as well as traditional or conventional small-scale farming, especially in developing countries. Even though the FAO of the UN has distinguished sustainable intensification as a suitable methodology for the improvement of smallholder horticulture (FAO 2011), the practices sketched out in "Protection and Growth" give small comprehension of the open doors offered by plant science, and they do not address the issues we face the scale or multifaceted nature of the creative challenge. Each of the four reports in some portion of the meeting is enormous scope extends that are as of now effectively associated with examination, training, and investigation of farming frameworks in underdeveloped countries. The three papers include authors from the United States and Africa, all of which show successful global participation that is basic to viable advancement.

6.7.3 Innovation for Sustainable Agriculture

Following the arrangement proclamation of the Royal Society and the report on the practical rural turn of events (Royal Society 2009), the papers in this area center around the improvement of farming by shielding crops from natural misfortune while limiting harvest misfortunes. Expanded insurance is fundamental with the goal that interest in land readiness, seeds, water, and supplements is not squandered. A definitive objective is to give improved assurance and lessen carbon impression through seeds while upgrading plant execution, atomic reproducing, and misusing species, assorted variety using friend plants, and hereditary adjustment (genetically modified; GM). The essential objective of this area is to underline the new sciences in this field, which will establish the framework for another worldwide rural framework.

The possibility to improve plant execution by utilizing plant enhancers or initiators as a medium, when applied to crops, will upgrade its essentialness, flexibility, and execution. From the proof of right now accessible mixes, (for e.g., the monetarily accessible compound benzothiazole-S-methyl and normal item laminarin), it tends to be seen that the arrival of increasingly more attractants can improve the parasite (that is, the parasite that slaughters its host). Protective organic control of herbivorous irritations (Sohby et al. 2014). Next is a portrayal of how to utilize hereditary screening techniques to recognize new ideal growth regulators.

6.7.4 Management of Agroecosystems Using the Framework of Ecosystem Services

The Millennium Ecosystem Services Report is a progressive distribution that has significantly affected science and strategy (MEA 2005). This technique has been exposed to a progression of public appraisals (Biggs et al. 2004; NEA 2011), and this system is broadly applied/considered for future land-use the executives' choices. Although there is banter about how best to clarify the "esteem" of assistance (Fisher et al. 2009; TEEB 2010), The idea of biological system administrations is increasing a significant political establishment, and even by lessening deforestation and woods corruption (REDD) and REDD emanations, assisting with forming thoughts identified with biodiversity balances (UK nature) and installments for environment administrations past carbon exchanging (Bond et al. 2009; Porras et al. 2013). It, without a doubt, gives a valuable structure to the improvement of ideas, for e.g., manageable farming turn of events and how to accomplish food security while nature is steady. It is identified with a few Millennium Development Goals.

Guaranteeing food security requires the concurrent arrangement of four fundamental difficulties. When searching for momentary arrangements, the flexibility/strength part is frequently neglected. This can prompt a "misfortune of the open area"and the loss of key administrations (Ostero Mu et al. 1999). This last arrangement of articles takes a gander at natural maintainability with regards to the food framework in the desire for attempting to “close the hole,” which is the fundamental focal point of the conversation meeting.

6.7.5 Agroforestry for the Provision of ESS and Sustainability of the Agriculture System

Agroforestry systems, have the potential to support climate-resilient production systems by considering both pillars of environmental fluctuations, i.e., strategies for adjustment and mitigation (FAO 2013). Agroforestry indicated the possibility of enhancing crop productivity in different regions, especially under tropical and temperate climatic conditions (Palma et al. 2007). It is successfully being used under different conditions and has the potential for adaptability and sustainable production (Bayala et al. 2015). Agroforestry is the innovative approach being sued to improve food security, mainly perennials contributed to soil fertility by increasing organic matter resulting in improved crop yields (Powlson et al. 2011). Different benefits are being received from trees under agroforestry system than mono-cropping as trees are the source of valuable timber, fodder, fruits, fuel and construction materials, and human nutrition (Lott et al. 2009; Jose 2012; Böhm et al. 2014; Burgess and Rosati 2018; Kay et al. 2019). Agroforestry has the possibility of contributing much better for sustainability as it can be used both for adjustments and alleviation of environmental fluctuations for the short and long term (Powlson et al. 2011; Luedeling et al. 2014; Abbas et al. 2017; Udawatta et al. 2019). Practices and strategies of agroforestry have shown an ability for the sustainability of resources and their management under different crop and land-use systems by promoting and conserving the ecosystem services (Dagar and Tewari 2018; Crous-Duran et al. 2019). Agroforestry has numerous advantages like to improve soil health and structure, better water infiltration and regulations, develop microclimate, promote ecosystem services, reduce soil erosion, improve the fertility and sustainability of soil, enhance carbon sequestration, effect the emission of GHGs, and source of finance for both short-and long-term growers (Jose 2009; Sistla et al. 2016; Beuschel et al. 2020). Contribution of agroforestry toward ESS provisions, sustainability, climate change mitigation, and adaptions depends on the components of an ecosystem, and site-specific response not only the positive impacts under each system in a short time, but it may also need a longer period (Torralba et al. 2016; Burgess and Rosati 2018).

6.8 Science and Technology for Food Security

Accomplishing food security by 2030 is said to be a significant test and will continue so all through the twenty-first century. The sustainability developmental targets including the rest of the other worldwide endeavors to accomplish food security utilize novel advancements as a fundamental device to terminate starvation. This part talks about how certain uses of science and innovation assume a job intending to different parts of food security. The key scientific scopes to adopt in food security includes accessibility, access, consumption, and sustainability. The application of science and technology in each step of the food production chain from farm to fork can enhance food production for the future (Asseng et al. 2014).

6.8.1 Improvement in Agricultural Productivity Through Science and Technology

FAO (2006) has diagnosed a gap of about 70% crop energy to be had in 2006 and predicted caloric necessities in 2050. To fill this gap, it's far essential to enhance genetics to enhance meal production, lessen meal loss, waste, and nutritional changes, and increase productiveness through the way of means of enhancing or keeping soil fertility, pasture productiveness, and re-establishing damaged land (Ranganathan et al. 2016). Thus, given the reduction of arable land, limited water resources, ecological and agronomic constraints, the food supply will have to narrow this food gap. Appraising the previous 40 years, approximately 33% of the cultivated area worldwide has been degraded due to contaminations or run-off.

6.8.2 Crop Production and Plant Varieties Improvement Through Conventional Cross-Breeding

Genetic amendment of plant sorts may be used for dietary fortification, drought resistance, herbicides, pests and diseases, and growth yield. In earlier styles the crop improvement concerned traditional breeding methods. In the mid-1800s, Gregor Mendel officially delivered a way that used nonstop generations of "relative crops" with the best breeding traits till the very last range fit the traits of the goal range. Though crop improvement is confined to the superior characteristics in the same crop family (Buluswar et al. 2014), this technique is still useful, especially for smallholder farmers in many areas.

6.8.3 Increase in Agricultural Production Through Genetically Engineered Crops

The genetic modification of crops through the insertion or deletion of genes from genetically distant organisms resulted in new crops with superior traits. Transgenic organisms have many benefits, inclusive of biotic stress resistance (pests, diseases), abiotic stress resistance (deficit water and salinity), progressed nourishment, flavor, texture, herbicide resistance, and decreased artificial fertilizer inputs. With current issues of water shortage and growing depletion of agriculture land, such technology doubtlessly improves productiveness in keeping with a unit of land or factory. Many countries, which include Bulgaria, are growing the abilities of those present-day agricultural biotechnologies through their Institute of Plant Physiology and Genetics to enhance crop resilience to environmental stress. Notable examples of present-day genetically changed vegetation include:

- Bt-cotton in India and China and Bt-Maize in Kenya1311
- Disease-tolerant as well as early maturing *Zea mays* cultivars that drove maize yield in Nigeria in the 1980s
- Nigerian cassava resistant to cassava mosaic virus that improved production in the 1990s
- New Rice for Africa (NERICA) rice genotypes that are hybrid mixtures of African and Asian rice species
- Banana *Xanthomonas* wilt
- Bt-Brinjal (*Solanum melongena*) in Bangladesh
- *Maruca vitrata* (developed by Nigerian scientists)
- African Orphan Crops Consortium that arranges African indigenous crop plants
- The NextGen Cassava Project uses genetic assortment to improve crop productivity (Buluswar et al. 2014; World Bank and FAO 2009).

6.8.4 Crop Yield Improvement Through Soil Management

For decades, artificial fertilizers had been used to improve agricultural production, however, their investment reliance on herbal fume (mainly with inside nitrogen), and big biological footprint of such sources lead them unsustainable. Excessive use of fertilizers and water can motive environmental harm and monetary waste to smallholder farmers. In addition, the Intergovernmental Soil Technology Group established soil as a nonrenewable resource by considering frequent soil mining (ITPS 2015). Many novel knowledges are assembling extra viable manure use possible. Novel techniques that keep away from using contemporary constant properties and energy-in depth techniques of nitrogen fixation and different fertilizer additives could make dietary supplements extra environmentally sustainable. A current observed that nitrogen-solving timber inside important water and temperature thresholds could boom yield through growing soil water-keeping capability and water permeability (Folberth et al. 2014; United Nations 2015a, b). For example, “N2Africa” is a large-scale, science-primarily-based development-to-studies mission committed to making use of nitrogen fixation generation to small-scale growers developing pulse vegetation in Africa (Giller et al. 2009).

6.8.5 Availability of Water for Food Production Through Irrigation Technologies

Light-weight drilling rigs for shallow groundwater and system for detecting groundwater can also additionally make it less complicated to achieve groundwater through irrigation. Solar irrigation pumps can also additionally grow the possibilities of irrigation. In this case, guide irrigation pumps that can be tough to apply are not enough, or pricey electric-powered pumps and gas charges are financially unaffordable (Buluswar et al. 2014). Inexpensive facilities for rainwater harvesting also are an ability generation to resolve irrigation problems (UNCTAD 2010). Where diesel or sun pumps cannot be used, hydraulic pumps (inclusive of the aQysta Barsha pump) could be adopted for watering with the availability of water streams. Greenhouses can alleviate water shortages as a result of inadequate precipitation allowing farmers to have a year-spherical developing season. For example, the modern greenhouse fuel line output (GRO) that the sector hopes will permit farmers to construct low-fee greenhouses in Sierra Leone and Mozambique in only days over a length of 5 years (UNCTAD 2011).

6.8.6 Increasing Regional and Global Stage Agricultural R&D Investments

Local and international agricultural research and development may have an actual effect on the productiveness and best of inputs. The ever-converting ecology, surroundings, and biodiversity surroundings call for nonstop studies and improvement to generate inputs and disseminate know-how to maximize agricultural manufacturing at the same time as protective of the surroundings. Government-funded R&D sports improved via way of means of 5.5% in line with years among 1995 and 2000, and improved via way of means of 15% in line with year after 2000, and are taken into consideration to be the important thing to negative farmers' adoption of superior technologies (UNCTAD 2015). Globally, FAO, IFAD (International Fund for Agricultural Development), and WFP (World Food Programme) estimate that casting off starvation via way of means of 2030 would require an extra US$267 billion in line with the year (United Nations 2015b; FAO 2015).

6.9 Challenges for Adaptation of Next-Generation Input Management Technologies

The yield of staple crops is reported to slow down, but in the next 33 years, more food is expected than in 10,000 years since the agricultural revolution started as it is influenced by population increase, dietary change, climate change, environmental degradation, etc. (Sustaining Food Availability 2020). Among these, climate change is a major constrain of transition for food security in the world, since it affects food development and its stability, as well as other facets of food systems, such as transportation, food distribution, and usage (Wheeler and Von Braun 2013). Furthermore, to adopt a holistic approach to the food production of welfare, the objectives of agricultural production, health, and nutrition security are summarized together (Fig. 6.4). Climate change's impacts intersect with other patterns of change from local to global fiscal, political, temporal, and biophysical aspects. These changes are distinguished by contradictions in the implementation of sequential and unilateral policies (Kriegler et al. 2012; Vervoort et al. 2014). Thus, the challenges to ensure sustainable food safety are structural, thereby decision-makers should take serious system-wide steps (Vermeulen et al. 2013).

In this context, an exceptional process reached its decision in 2015; with an agreement of eco-friendly sustainable development for the betterment of future manhood (i.e., 2030 Agenda for Sustainable Development). This agenda articulates a common and coordinated application action plan in all countries (both developed and emerging) through 17 sustainable development goals and 169 targets (UN 2015a). Thus, these need to combine all aspects of ecological growth across all to set viable development goals (Caron et al. 2018).

6.9.1 Major Challenges

The main challenges for the adaptation of next-generation input management technologies are discussed with complete details in Table 6.2.

Thus, the above provided the summary of above-mentioned major challenges for adaptation of next-generation input management technologies. All of them are directly and/or indirectly associated with each other. For example, poverty, food security, and nutrition narratives have become increasingly part of the food systems and are inherent in rural economic growth. Consequently, modernization of all upcoming farm activities could be predicted.

6.10 Conclusion

Under changing climate and rapidly expanding human population, crop yields need to be multiplied by intensive utilization of existing traditional farming. However, intensive farming systems utilizing imbalanced doses of synthetic fertilizers and pesticides have caused environmental pollution. Overexploitation of natural resources has posed serious threats to food security for future generations. Therefore,

Fig. 6.4 Schematic presentation of main factors of sustainable food generation (Modified from Pingali et al. 2019 with permission)

Table 6.2 Summary of key challenges aimed at adaptation of next-generation input management technologies

S. no	Main challenges	References
1.	*Increased food demand and sustainable agricultural production* To satisfy the expected dietary requirements according to global demand and the continuing change to wealthier foods, some estimates indicate that world food production needs to be doubled by 2050. It is now a critical challenge to fulfill global food requirements with the means of safe and nutritious for the rising population. The key priority of today's agriculture should, therefore, be to increase crop production by protecting the atmosphere and mitigating adverse consequences of climate change. Thus, sustainable intensification can be the preferred solution to global food security issues, increasing crop yields while reducing their environmental impact, thus ensuring future generations' ability to use the land. Because the use of improved cultivars, irrigation, the applications of chemical fertilizers and agrochemicals to increase yields, etc. are demarcated as traditional agricultural practices which are reported to be responsible for the overuse or abuse and degradation of the field and environmental contamination, as well as adverse effects on human, plant, animal, and aquatic ecosystems. therefore, the generation of nutritious and affordable food, restoration of soil fertility, and climate change mitigation are suggested as keys to sustainable food production	Davis et al. (2016), Kumari et al. (2018), Timsina (2018), Beltran-Peña et al. (2020)
2.	*Climate change and acceleration in natural hazard incidents* One of the challenges for the next adaptation of next-generation input management technologies is climate change and other aspects of environmental deterioration. Currently, humans are consuming 1.7 times more energy than the earth can regenerate and consume and creating more wastage. Thus, there is an exploitation of tomorrow's resources, knowingly or unknowingly. Furthermore, due to this imbalance, there was an increase recorded the incidences of natural hazards that are also affecting food production	Global Footprint Network 2017; Wheaton and Kulshreshtha (2017), Ritchie et al. (2018), Montt et al. (2018), del Pozo et al. (2019), Ruhullah et al. (2020)

(continued)

Table 6.2 (continued)

S. no	Main challenges	References
	For examples: (a) According to the study of Wheaton and Kulshreshtha (2017), a rising frequency of extreme climate, including drought, heat waves, and excess rainfall, are expected in the future (b) A study reported the impact of global dietary guidelines on the greenhouse gases emission and revealed that the existing recommendations at the national level are highly discordant with a target of 1.5 °C as well as also incompatible with a budget of 2 °C unless other sectors are completely decarbonization by 2050 (Ritchie et al. 2018) (c) The adaptation of agricultural products to environmental deviations in the five Mediterranean-climate regions of the world requires the synchronized strategies covering the various organizational levels, i.e., crops, cropping methods, and farming system (del Pozo et al., 2019) (d) In the study of Ruhullah et al. (2020), evidence showed that the Climate Change Assessment Initiatives in Bangladesh could be successful in partnership with the United Nations development programs	
3.	*Poverty and inequality* In international debates over the years, the double issues of environmental pollution and poverty have become a great deal of concern because of challenges pertaining to the viable growth in the world. A case study from Nigeria revealed that rural poverty and unstainable practices contributed to the instantaneous environmental effects and even adversely impacted resource management. Furthermore, according to sustainable development goal 1 (SDG 1), by 2030, extreme poverty should be eradicated from everywhere who are living less than 1.25$ per day	Imai (2017), Nwokoro and Chima (2017)
4.	*Hunger and all forms of malnutrition* Global hunger is persistent in over 800 million, while micronutrient deficiency is over 2 billion. The cause of malnutrition is physical and mental illnesses, a variety of infectious diseases, and premature deaths. Therefore, actions on multiple types of malnutrition are generally taken by	FAO (2019), Qaim (2020).

(continued)

Table 6.2 (continued)

S. no	Main challenges	References
	different laws, policies, initiatives, communities, governance, and funding sources, etc. the SDG two aims to stop all types of malnutrition as well as to end hunger along with doubling farm production and small-scale profits to ensure sustainable food production	
5.	*Making food systems more efficient*: According to scientific literature, there is evidence that food systems are important for sustainable development as they are linked to food protection, nutrition, and human health, ecosystem sustainability, climate change, and social justice. As per the observations of recent work, the new plant breeding technologies offer great possibilities to contribute toward stabilized crop production and dietary safety. Furthermore, the dietery systems comprise all the fundamentals and activities that are related to food production, distribution, food preparation, and use, consumer and institutional networks regulating these activities and their socioeconomic and environmental outcome	Caron et al. (2018), Ruben et al. (2018), Qaim (2020)
6.	*Improvement in earning opportunities:* Sustainable crop production sometimes could not provide enough economic benefits. This statement was found correct as per the finding of Zeweld et al. (2020), which stated that the livelihoods of farmers and rural households in mainly agricultural economies could be hard to boost without destroying natural resources. Moreover, climate change is reported as the key constrain that affecting the livelihood of farmers	Saina et al. (2013), Zeweld et al. (2020)
7.	*The requirement of logical and vigorous authority locally and globally*: The food protection and commerce law and regulation have grown with the maturation of food production processes and the extension of foreign trade. The legislation that was acting at national levels has traditionally been created and resulting in jurisdictional differences. Moreover, the global food trade has risen to over 520 billion dollars annually, thus adding new challenges to the regulation on global food safety for the coherence at local and worldwide	King et al. (2017)

next-generation input management in traditional farming is very crucial for sustaining future food and environmental security. This can be achieved by the integration of land, pest, disease, nutrient, and other resource management practices. Adoption of next-generation plant breeding approaches, judicious application of water and fertilizers in crop production systems, environment-friendly crop protection practices, eco-friendly soil and land management systems, and systematic integration of different disciplines hold great promise to avert nutritional food insecurity and environmental degradation.

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Reduction of Energy Consumption in Agriculture for Sustainable Green Future

7

Sandeep Kumar, Shiv Prakash Singh, Ram Swaroop Meena, Shivani Lalotra, Ritesh Kumar Parihar, and Biplab Mitra

Abstract

Ever augmenting population pressure and energy crisis are twin challenges for the food environment, and economic security. Green revolution marked the agricultural production in India due to the intensive use of fertilizers, pesticides, irrigation and mechanization pressure, which leads to high energy consumption pressure. Escalated energy demand has also driven the GreenHouse Gases (GHGs) emission that remains a threat for green future. Therefore, urgent need to identify the traditional agricultural practices to reduce energy consumption and improve the Energy Use Efficiency (EUE) through the best management practices. This chapter is focusing on reducing energy demand and enhances the EUE. Many practices are recognized as effective for sustainable green energy use with better resource utilization patterns. Resources efficient and conservational technologies for best and alternative use of power, fuel, seed, nutrient, water, electricity, management practices, etc. need be adopted. Conservation

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agriculture (CA)-based cropping with legume and residue retention, integrated use of available resources, combining agriculture with forestry and animals, efficient postharvest operations and transporting, reducing dependency on nonrenewable resources are sustainable and energy-efficient approaches for the green future. It will help producers, researchers, policymakers, and the government planners to make a roadmap for the green future and advance sustainability.

Keywords

Agriculture · Energy consumption · Energy use efficiency · Policies

Abbreviations

%	Percent
ai	Active ingredient
$b\ d^{-1}$	Barrel day^{-1}
BU	Billion units
CA	Conservational agriculture
CT	Conventional tillage
DSR	Direct seeded rice
EUE	Energy use efficiency
FYM	Farm yard manure
GHG	Green house gas
GJ	Giga joule
ha^{-1}	Per hectare
INM	Integrated nutrient management
K_2O	Di-potassium oxide
kg	Kilogram
kPa	Kilo Pascal
KTOE	Kilo ton oil equivalent
kWh	Kilo watt hours
LCC	Leaf color chart
LMT	Lakh metric ton
m^3	Cubic meter
Mha	Million hectares
MJ	Mega joule
MT	Metric tons
Mt.	Million ton
MTOE	Million ton oil equivalent
MW	Mega watt
MWh	Mega watt hours
N	Nitrogen
NDVI	Normalized difference vegetative index
NUE	Nitrogen use efficiency
P_2O_5	Phosphorus pentoxide

T	Ton
TOE	Ton oil equivalent
TWh	Terra watt hours
WUE	Water use efficiency

7.1 Introduction

The world population is on the rise and the existing trend of the escalating population will be expected between 8.3 and 109 billion by 2050 according to the UN organization estimates (Prosekov and Ivanova 2018). About 50–75% increase in the food supply will be required to feed the rapidly mounting global population depending upon the region (Prosekov and Ivanova 2018). This augmented population growth rate has posed serious threats to agricultural and environmental sustainability as well as global energy consumption. Moreover, the changing climatic scenario has become a real observable fact that directly or indirectly puts pressure on already overexploited existing natural resources and offer somber challenge to global food security. The world food production is mainly challenged by two major factors, i.e., climate change and energy consumption in agriculture which became talk-of-world now a days. These twin factors have direct impact on agricultural yields and challenge global food security. To produce sufficient food for the increasing population, agricultural intensification is increased in the existing cropland which ultimately put environmental sustainability at stake and energy consumption at the pinnacle. About 30% of global energy consumption is through the agriculture and food industry (FAO 2011). Meanwhile, energy consumption is directly affected by the changing climatic scenario. More the impact of climate change more will be the energy consumption in adjusting the whole agricultural methodology for cultivating a particular crop.

The pre-green revolution era utterly relied upon human and animal power for operating traditional tools and implements where commercial energy consumption was almost negligible. Rise in food demand increased the competition for water, land, and inputs to produce sufficient food. Moreover, agriculture sector requires huge energy and inputs to meet the global food production as agriculture being a production-oriented sector. In the post-green revolution era, initiatives and steps were taken by successive governments to reinforce the agriculture sector by increased use of inputs (fertilizers and pesticides), development of packages and practices for sowing crops, investments in building and irrigation infrastructures at farms, etc. Strengthening the agriculture sector requires the direct or indirect use of energy at each level in the farms.

7.1.1 Direct Energy

Gasoline, natural gas, electricity, diesel-and petroleum-based fuels are chiefly considered as direct energy consumption sources and are used directly in the farm. Diesel-and petroleum-based energy sources are mainly used for the transportation (tractors, combine harvesters, trucks, etc.) of off-farm inputs and outputs, harvesting crops, operating machinery for preparing fields, sowing, transplanting, spraying pesticides, etc. Electricity consumption is possible at each farm level, i.e., operating irrigation pumps, lighting, cold storages, greenhouses for maintaining temperatures, operating machinery for drying, postharvest packaging and processing, milking machines in the dairy sector, etc.

7.1.2 Indirect Energy

The activities that are operated off the farms like fertilizers and pesticides manufacturing, chemicals (for scientific researches) and inputs production, manufacturing of farm machinery and equipment consumed indirect energy. Besides these oils and lubricants were also used for farm machineries and equipment's maintenance.

Agricultural sector uses both direct and indirect energy for cultivating crop, livestock and postharvest value additions, and operations. For the growth of the agriculture sector, several policies and initiatives were taken into consideration by the government. In which, the government and private sectors worked jointly and realized the importance of agriculture. This led to an increase in the level of mechanization over the years ultimately results in total energy consumption (direct and indirect energy) in the agriculture sector.

7.1.3 Global Energy Use Pattern of Agriculture

The world's total energy consumption accounts for about 553.9 MTOE and is expected to grow in the future due to ever-escalating population (ES 2019). China is the largest energy consumer in the world followed by the America and India. Globally, the agriculture sector including fishing consumes about 2.07% of the total world's available energy in the form of electricity, coal, and oil (Fig. 7.1). Electricity consumption in agriculture sector has increased from 29,478 KTOE (1990) to 58,873 KTOE (2018) but share remains steady (3%) with an increasing demand over various demanding sectors (IEA 2019). Coal contributes to be the largest share for electricity generation in all demanding sectors and accounts for 38% of total electricity generation compared with other sources of power generation (BPSRWE 2019). The increasing demand for electricity indirectly put pressure on exploiting coal. The oil consumption also shows an increasing trend with an average of 1.4 million b d^{-1} (BPSRWE 2019). Total crude oil consumption in the agriculture sector increased from 1,04,939 to 1,11,062 KTOE during the years 1990 to 2018. Now, the

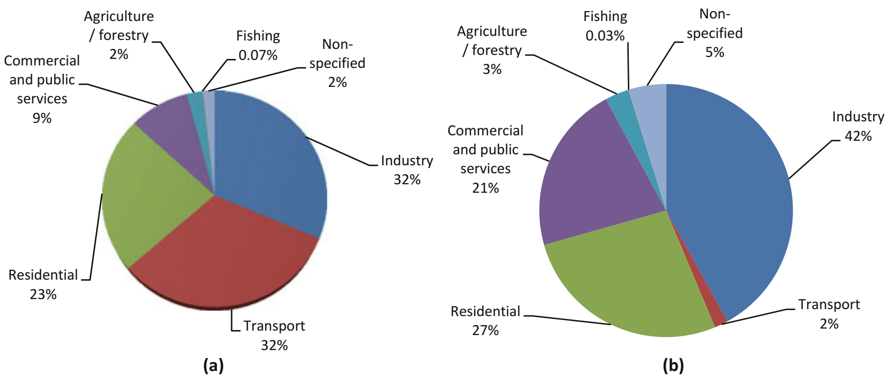

Fig. 7.1 Sector-wise (**a**) energy and (**b**) electricity consumption of the world in 2018 (Source: ES 2019; IEA 2019)

agricultural sector accounts for 15% of the total world's oil consumption and demand is likely to increase in future (IEA 2019).

7.1.4 Energy Use Pattern in Indian Agriculture

India stands among top energy-demanding countries in the world. Further, energy use is highly increased in each demanding sector by virtue of its growing economy; about 11% increments in total energy demand is expected by 2040 (BP 2020). At the same time, the energy production cost is increasing at a faster rate. Energy intensity of India is facing rapid dwindle; 65.5 TOE/Cr Rupees in 2011 to 55.8 TOE/Cr Rupees in 2018 (BEE 2019). Meanwhile, per capita, energy consumption trend in demanding sectors is also at a peak from 0.466 TOE to 0.559 TOE during this period.

Agriculture is the most important sector in energy consumption; contributing about 5% of the total energy supplied (Fig. 7.2). This showed hasty augmentation in energy demand by twofold in the last decades due to commercialization and diversification (Fig. 7.3). Indian agriculture also consumes the huge amount of electricity 18% (203BU) and demand is growing rapidly; potentially tripled in future. This increasing demand is owing to the modernization of inputs, machines equipment and modern technologies. Agriculture stands third major electricity consumer sector after industrial and residential sectors (Fig. 7.2). Meanwhile, the government of different states provides mostly free or high subsidies electricity for agricultural purposes but the farmers pay less attention in saving energy.

Electricity, the direct energy source is obligatory in farms due to mechanized crop or animal equipment and ensures timely energy supplies at each level of the production cycle. This holds true for maximum profits at farms and timely management of climacteric and non-climacteric commodities. In 2018, agricultural electricity consumption in India accounts for about 18,195 KTOE (Fig. 7.3). In 1990, even

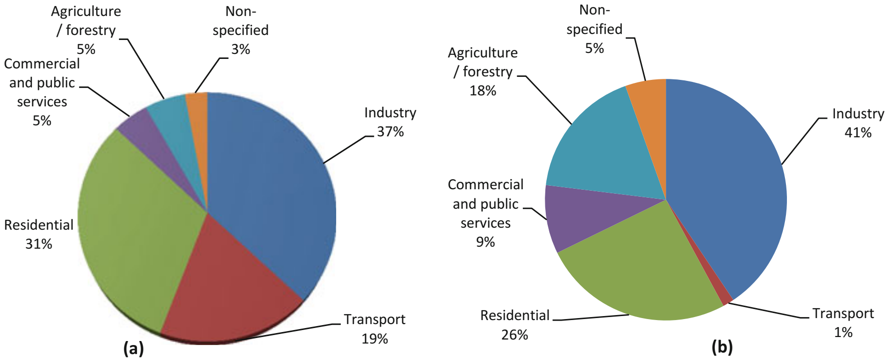

Fig. 7.2 Sector-wise (**a**) energy and (**b**) electricity consumption of India in 2018 (Source: IEA 2019; BEE 2019)

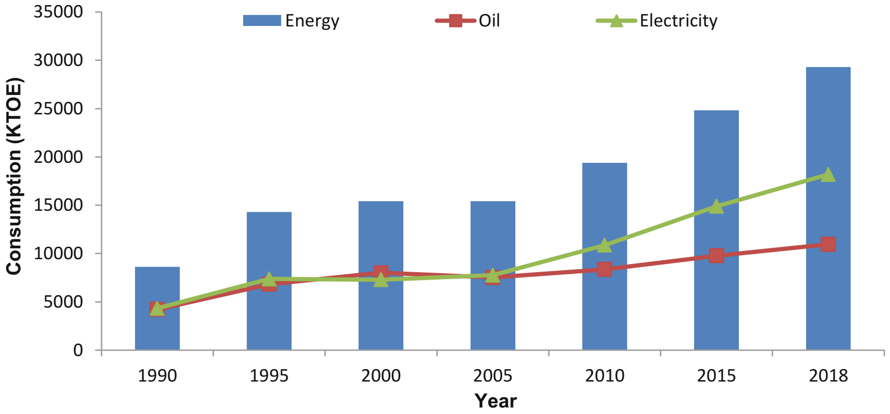

Fig. 7.3 Energy use trend of Indian agricultural sector in past three decades (Source: BEE 2019)

though in the post-green revolution era, there is an even out demand for electricity that accounts for 4327 KTOE in the agriculture sector compared with other demanding years. Thereafter, trend of electricity consumption in the decades 2005 to 2018 witnessed a sharp increase and had been swinged from 4 digits to 5 digits (7764 KTOE to 18,195 KTOE). Based on current data, India's electricity demand in agriculture sector will rise further and could be tripled by 2040, with potentially used agro-production chains, cold storage infrastructures, farm machineries, chaff-cutters, root-cutters and irrigation tube wells/pumps. India's per capita electricity consumption also stands from 2.06 to 3.26 MWh in the decades from 1990 to 2018 (GOI 2020a). Industrial sector is also involved in the production process of farm-based equipment and machines, pesticides, fertilizers, phytohormones, chemicals, and agricultural inputs together representing 41% of total electricity consumption as depicted in the pie-chart (Fig. 7.2). It has been reported that demand of the agricultural sector for energy, electricity, and oil is consciously increasing. Therefore, achieving energy efficiency along with reducing energy consumption are twin challenges that needs to be achieve nowadays.

7.1.5 Need for Achieving Energy Efficiency

Direct energy demand hits the highest point in the past few years in each demanding sector. The demand for sequestered energy inputs (indirect energy inputs) like fertilizers, herbicides, pesticides, and insecticides also increased due to large-scale commercial farming. The production, distribution, and transport processes of these inputs also require energy. Fertilizers and pesticides are most energy-intensive agricultural inputs as these inputs became the preferred ones in each cultural practice of crops. Nitrogen is the principal fertilizer and its production process requires a huge amount of energy. Urea is predominately preferred and production is more; India producing 249.25 LMT (GOI 2020b).

Besides fertilizers, irrigation is the principle input for sustainable food production; about 60% of food grain production is owing to utilizing groundwater. Energized pump sets are used by the Indian farmers for pumping groundwater for an assured source of irrigation. A total of 21.3 million energized pump sets are available in India (CEA 2019). Broadly speaking the calculation of energy consumption by an energized pump set was 6004 kWh of electricity annually (CEA 2019). Indian farmers are getting insufficient electricity supplies at farms for which they use diesel pump sets as a standby in commercial farming. Therefore, diesel demand in the last two decades was also increased in the agricultural sector. Similarly, tractors, combine harvesters as well farm practices right from sowing to harvesting and postharvest operations required a huge amount of nonrenewable energy. Therefore, consumption of both direct and indirect energy increased in decades.

It is cleared from aforesaid facts and figures that both direct and indirect agricultural energy consumption in the world and India is at peak. Industrialization, urbanization, and increased mechanization in agriculture marked the higher demand of both renewable and nonrenewable energy resources from time immemorial. In view of this, energy efficiency is need of time and is a win–win strategy. Since, we are on the verge of the energy crisis, the efficient use of energy in agricultural sector assumes importance. In this chapter, attention to agricultural enterprises, practices and policies, are considered to solve this huge crisis. Direct and indirect energy use patterns along with efficient technologies and approaches are discussed in further sections.

7.2 Traditional Farming and Energy Use

7.2.1 Crops and Cropping System

The agricultural productivity and food sustainability are regulated by appropriate cropping system in a particular agroecology. Energetics of cropping/system is directly linked with the productive potential of crops and varieties. Energy analysis in terms of efficiency and its use in a cropping system provides effective and equilibrated use of agroecological resources. Though along with crop, the high yielding varietal selection also affects energy dynamics. Numerous reports across the globe indicated the effects of cropping patterns and its management. Input intensive crops like rice, wheat, maize, etc. consume more energy while their productive potential affects the energy productivity. A good relationship between the energy input–output process offer opportunity in balanced crop production with the least specific energy and carbon footprints. Energy cost and crisis are increasing nowadays and make agriculture less profitable due to high production costs (Jha et al. 2012).

Jha et al. (2012) indicated energy cost of different crops; cost of cereals (rice, wheat, and maize) was higher (10–13 thousand rupees ha^{-1}) than millets (pearl millet, sorghum), oilseeds (rapeseed and mustard, soybean), and pulses (pigeon pea, chickpea). Input intensive crops and varieties have high energy requirement and energy costs. Commercial crops like cotton, potato, and sugarcane had much higher energy cost (Jha et al. 2012) than cereals due to additional tillage, fertilizers, human labor, etc. Crops differed in water requirement besides other inputs. Water guzzling crops also enhance energy use for pumping more water and has higher energy cost like rice; 47.8 MJ US\$$^{-1}$ (Singh et al. 2020a). Crop energy requirement also varies due to extend of mechanization and human labor use. In spite of lower mechanization index of maize, it needs more input energy than wheat, rye, and rapeseed (Alluvione et al. 2011) due to continuous engagement of human labor for various intercultural operations like weeding, earthing-up, and harvesting, etc. Howbeit the efficiency of input energy conversion of maize is more than soybean due to better productive potential. In a comparative study of cluster bean, maize, cotton, wheat, and mustard total least energy input was achieved in cluster bean and highest in cotton (Singh et al. 2003). Input energy not only varies with crops but also with the locations; wheat grown in western Rajasthan requires more (17–20%) energy than Madhya Pradesh, Uttar Pradesh, and Punjab (Singh et al. 2007). Rajasthan is a relatively dry area where irrigation cost is more. Energy demand patterns also differed in horticultural crops. Among the vegetable crops, tomato and chili require more input energy than lettuce (Kuswardhani et al. 2013). Pepper has paralleled energy demand with tomato, cucumber, and eggplant but theefficiency of conversion during the production process is less (Canakci and Akinci 2006). Citrus production in Turkey suggested that mandarin requires less total energy than lemon and orange while indirect and nonrenewable energy consumption is more in lemon (Ozkan et al. 2004).

Table 7.1 Energy use pattern of different cropping systems

Cropping system	Input energy (GJ ha^{-1})	Energy output (GJ ha^{-1})	Energy ratio	References
Double cropping				
1. Cereal-cereal				
Rice–Rice	65.4	183.9	2.8	Shilpa et al. (2018)
Rice–oat	11.2	78.2	6.9	Kumar et al. (2016)
Rice–wheat	25.6	191.7	7.4	Singh et al. (2019a, 2020a)
Rice–buckwheat	5.9	22.4	3.8	Banjara et al. (2019)
Maize–wheat	22.6		3.11	Gosh et al. (2015)
2. Cereal–legume				
Rice–chickpea	4.5	24.7	3.8	Banjara et al. (2019)
Rice–lathyrus	3.7	25.4	6.9	Ganajaxi et al. (2011)
Soybean–wheat	13.4	23.7	5.5–7.5	Mandal et al. (2002)
Groundnut–wheat	22.2	183.8	8.3	Ganajaxi et al. (2011)
3. Cereal–oilseed	3.7–6.3	22.3–53.9	6.1–8.5	Banjara et al. (2019)
4. Legume–legume	15.7–19.8	92.7–175.5	5.9–8.9	Ganajaxi et al. (2011), Singh et al. 2008
Multiple cropping system				
With legumes	13.5–13.6	194.0–341.9	14.2–15.3	Pooniya et al. (2015), Yadav et al. (2016), Khan and Hussain (2007)
Without legume	31.9–39.9	373.9–403.8	9.4–12.6	Khan and Hussain (2007)

Disparity of energy consumption among various crops could alter by efficient cropping system. A combination of crops in a cropping pattern and its management is equally clarifying the energy consumption, its conversion in usable form. Various literature on energy budgeting in a cropping system indicated that cereal–cereal cropping is least beneficial and require more energy with lesser EUE (Table 7.1). Rice–wheat cropping system covers highest area in the northern India (13.5 mha) and exploits huge energy and natural resources. Diversification and intensification of cropping systems is important management practice. In terms of good energy conversion, cereal-legume or cereal-oilseed cropping system is valuable for energy balance and ecological sustainability. Inclusion of legumes in the cropping system required lesser nutrient and input demand with efficient utilization of available resources. Energy input–output analysis of various multiple cropping systems indicated that taking more crops in a year requires more input energy (13.5–39.9 thousand MJ ha^{-1}) than double cropping. However, utilization of input energy

(EUE) was high suggesting if all available resources are not scarce, we must take multiple crops on farm. This indicates better energy output of intensified cropping system. On the whole, it must be said that inclusion of legumes in multiple cropping and oilseeds in double cropping is more efficient and advantageous practice in terms of energy ratio and energy utilization during cropping process. However, cropping intensification through the inclusion of legumes is the foremost and energy consumption practice and is a major concern.

7.2.2 Tillage and Land Preparation

Indian agriculture is associated with heavy use machineries for intensive tillage (Gupta et al. 2016). Energy-intensive tillage is the major concern for global greenhouse production as it directly uses a high amount of direct and nonrenewable energy sources (diesel). During the post-green revolution era, mechanization became popular among farmers to obtain good tilth and friable seedbeds. Therefore, demand for fossil fuel drastically increased with the use of tractors. Heavy fuel demand in tillage leads to emission of CO_2; which has curtailed to half by 2050 (IEA 2013; Ethrel et al. 2015). Efficient energy use in agriculture is of prime importance without affecting productivity and food security of livelihood. Economics of crop production is highly related to energy consumption (Lu and Lu 2017). Tillage and crop establishment not only contributes 25–30% of crops production cost but also consume a high amount of energy, i.e., 10–29%, depending upon crop and intensification of mechanization (Saharawat et al. 2011; Pathak et al. 2011; Kumar et al. 2013; Jha et al. 2012; Shilpa et al. 2018). Direct energy cost in tillage could be escalated by the adoption of alternative methods or reducing its intensity.

Efficient machineries and curtailing mechanization index in crop production could save energy by 18–83% (Sørensen and Nielsen 2005; Mandal et al. 2015a, b). Conservational agriculture is an alternative strategy to reduce energy consumption in tillage operations as well as reducing the cost of cultivation (Balwinder-Singh et al. 2011). CA results in improved yield in terms of good soil health, aeration, and water holding capacity (Hamzei and Seyyedi 2016). Conservational tillage can enhance net energy gain and reduce net global warming potential (Ghimire et al. 2017; Lu and Lu 2017). In an experiment at western Uttar Pradesh, India; the sowing of wheat in rice–wheat cropping system through zero-tillage achieved 5–20% higher EUE due to 10–13% lesser energy demand and 3–5% higher energy output over conventional tillage and rotavator tillage (Kumar et al. 2013). Similarly, Hamzei and Seyyedi (2016) advocated the use of conservational tillage for higher EUE due to reduced energy inputs over conventional tillage. Residue retention in no-till maize requires 29.23% lesser nonrenewable energy than moldboard tilled planting while achieving 16.4% higher EUE (Lu and Lu 2017). In the same way, Nath et al. (2017) reported higher net energy returns (14.9%) and energy productivity (8.2%) with zero-tilled wheat sown with residue retention whereas, in mung bean, the increments were 14.9 and 8.0%, respectively. Conservational tillage practices always play an important role in reduction of energy demand (0.8 to

Table 7.2 Input energy reduction (%) in conservational tillage practices over traditional

Crops/cropping system	Zero tillage	Reduced/minimum/ raised bed	Rotavator	References
Pigeon pea	30.5	15.2	–	Pratibha et al. (2015)
Castor	31.3	11.5	–	
Wheat	3.5–13.06	10.5	0.8–10.9	Singh et al. (2020b), Kumar et al. (2013)
Maize	24.8	25.5	–	Yadav et al. (2016)
Maize–wheat	80.0	50.0–60.0	–	Sharma et al. (2011)
Soyabean–wheat	28.4	10.8	–	Singh et al. (2008)
Soyabean–lentil	29.9	9.0	–	
Soyabean–pea	37.3	13.8	–	

80.0%) over conventional practices (Table 7.2). However, zero-or no-tillage for all crops and cropping systems are more efficient in energy saving than reduced or minimum tillage while maintaining ground cover and reducing GHG emission from agricultural soil as well. In the nutshell, it must be important to say that conservational tillage with the right methods of sowing; mean a lot in reducing the energy demand and carbon footprints.

7.2.3 Methods of Sowing

Crops sown with various methods perform differently with energy budgeting. Methods that need more human labor along with intensive mechanization consume a high amount of direct and indirect energy. For example, rice required more energy when transplanted in conventionally puddled soil due to heavy use of tractors in puddling and human labor in transplanting (Banjara et al. 2019). Reducing energy demand by lowering mechanization and labor demand is a prominent approach. Bhushan et al. (2007) advocated no-tilled DSR for lower machine labor as well human labor in rice establishments. Therefore, direct energy as well nonrenewable energy (fuel) cost must be low. Human labor has input energy equivalent to 1.96 MJ hour^{-1} (Shahin et al. 2008; Kumar et al. 2013). Conventional wheat sowing practices required more input energy (1.1 GJ ha^{-1}) than direct drilling in soil (0.3 GJ ha^{-1}) and produced 22.4% lesser energy output (Arvidsson 2010). Wheat required lesser total energy input if sown in furrow irrigated raised bed techniques or zero-till drill in soil. The energy requirement for zero-tilled drill sown and on furrow irrigated raised bed wheat were 9–13% lower in IGP belt of India (Kumar et al. 2013).

It is obvious that, the benefit of direct drilling of seeds in soil had lower energy requirement due to negligible/less draft and fuel requirement. Direct drilling of rice seeds in soil is the utmost promising technique in terms of energy saving owing to bypass the energy requirement in nursery culture, puddling operation, and transplanting either with transplanter or human labor. The DSR techniques save about 22% energy input compared to transplanting (Mandal et al. 2015a, b). Use of machineries for rice transplanting significantly uplift the energy requirement by 17% over traditional manual transplanting; even 80% higher nonrenewable energy requirement. System of rice intensification had higher energy requirement than DSR but was able to achieve higher energy use efficiency (10.91) than mechanical transplanting (8.58) of rice (Mandal et al. 2015a, b).

Human labor requirement in rice sowing/transplanting has a significant role in energy requirement (Saharawat et al. 2010). Crop establishment of rice and wheat are different from each other. In general, rice required higher mechanization as well human labor (70–72%) than wheat cultivation in India. Traditional methods of wheat cultivation are energy-intensive practices due to higher draft force requirement in conventional rice–wheat cropping pattern. Newly developed happy seeders for wheat establishment are now gaining importance and provides opportunity of direct seeding of wheat in standing rice stubbles leftover in field. A single operation of seeding and bed preparation by a happy seeder could able to save about 50–70% fuel requirement than conventional methods (Singh et al. 2020b).

7.2.4 Crop Residue Management

India produced a huge quantity of crop residue (500Mt) every year; of which about one-third is being burnt on farm and accused of significant environment quality deterioration (Chen et al. 2019; Zhao et al. 2020; Sarkar et al. 2020). Proper management of crop residue not only improves soil and environment quality but also enhance crop productivity. Conservational agriculture uses crop residue as a surface covering material and minimizes such negative impact on soil. A successful management opens new avenues for nutrient recycling in agroecosystem during decomposition, control erosion and pest, reduce crop water demand, and facilitated lesser or non-dependence on synthetic amendments (Zhao et al. 2020). In situ carbon sequestration in the soil through mulching or incorporation of residue in soil significantly reduced GHG emission through burning. Onsight residue burning is the major problem in Punjab, Haryana, and western U.P. of India in rice–wheat cropping system; about 25Mt of rice–wheat residue burning contributed to 0.05% of total GHG emission of India (Gadde et al. 2009; Sarkar et al. 2020) and emits about 37Mt of CO_2 along with 31,250 billion MJ energy losses.

Crop productive potential and energy use has a direct and positive correlation (Jat et al. 2020). Residue acts as the indirect energy source in crop energy inputs. These enhance soil fertility as it contains about 40% carbon which directly contributed in soil C enhancement. Conservational agriculture-based crop residue management could save about 3000 MJ of energy ha^{-1} (Sangar et al. 2005). It could also defy terminal heat stress in wheat (Kumar et al. 2018; Sharma et al. 2015; Singh et al. 2009; Lohan and Sharma 2012; Jat et al. 2020) which is the major problem in India especially in rice–wheat cropping system (13.5 mha) and able to reduce in situ burning.

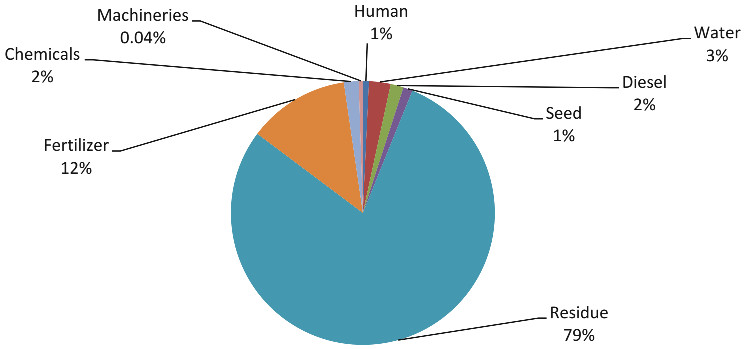

Fig. 7.4 Source wise share of energy input in conservational agriculture (Source: Jat et al. 2020)

Effective residue management may be possible through mulching, incorporation into the soil, composting, and CA-based residue management. The most effective and remunerative method is mulching; incorporation into soil requires heavy use of implements for chopping and mixing in the soil which inversely increases the energy demand (Jat et al. 2020). Crop residue could be also used for biochar, biofuel, and energy production. Crop residue has a potential of about 128 MW per Mt. per year energy production (Chauhan 2011, 2012). On the other hand, CA-based residue management required heavy machineries thus, energy input and output is more however, net energy could be higher (Jat et al. 2020). Crop residues contain about 12.5 MJ t^{-1} energy equivalent (Choudhary et al. 2017; Parihar et al. 2013); quantity of residue used for mulching significantly enhance the energy cost in agriculture (Parihar et al. 2018). It is well-known fact that residue retention or incorporation enhances the input use efficiency of crop and use a reduced quantity of inputs like fertilizers, water, pesticides, etc. Therefore, it indirectly contributes in the reducing total input energy demand of the crop (Parihar et al. 2018; Tomar et al. 2006). Total energy demands pattern of various components differs in CA-and CT-based residue management. In a five-year study, Jat et al. (2020) recorded the highest share of residue (79%) in total energy requirement in CA-based crop production if 80–100% stubbles of crop retained in the field (Fig. 7.4). Energy indices directly depend upon the quantity of residue retained on soil (Choudhary et al. 2017; Saad et al. 2016). CA-based residue management enhanced 23% energy input with only 44% increment in energy productivity over the conventional system because of higher productivity in CT-based residue management (Jat et al. 2020). However, in both systems, residue cover of about 4 t ha^{-1} significantly enhance the energy output but EUE and net energy return recorded higher in no-residue treatment (Choudhary et al. 2017). Mulching enhances energy output by 5–18% over no-mulching on the other hand, residue retention in conservational agriculture significantly lower down (12.7%) the total CO_2 emission as compared to residue incorporation in conventional agriculture (Yadav et al. 2018). Therefore, it is cleared that mulching is a highly important practice and has multiple roles in terms of weed management, soil moisture conservation, and ultimately reduce energy demand if used appropriately with management practices.

7.2.5 Weed Management

Weeds are the common obstacle in crop production resulting in 20–80% yield loss (Deike et al. 2008). Weed management implies different approaches in chemicals, degree of mechanization, machineries, human labor demand, etc. thus affecting the energy input. Effective weed management upshots the crop yield and enhances total energy output (Klingauf and Pallutt 2002; Deike et al. 2006, 2008). Use of herbicides nowadays gaining popularity in Indian agriculture; but the herbicides formation, its transport and formulation process indirectly use energy. Some of the popular herbicides used in Indian agriculture and their energy equivalents as shown in Table 7.3.

Though energy use of different weeds management practices in crop production accounted very low share (2–5%) in total energy demand (Jat et al. 2020; Deike et al. 2008). However, adopting a conservational tillage system facilitates large dependency on herbicide use; thus, may increase its share in total crop energy demand. On the other hand, CA-based tillage may itself curtail total energy input in agriculture by reducing tillage and diesel demand (Clement et al. 1995; Lu and Lu 2017; Singh et al. 2020a). Therefore, herbicidal usage in conservational tillage reduced energy input and enhances output on the whole.

Other weed management approaches like mechanical and manual need more energy. Conventional methods of seedbed preparation for reduction of weed pressure required 15–23% more energy than stale seedbed (Chaudary et al. 2006). Hand weeding is the labor consuming practice in contrast to mechanical methods, thus needs more renewable energy but less nonrenewable energy (Wood et al. 2006; Deike et al. 2008). Mechanical weeding on the other hand required more total energy input (Devi et al. 2018). Similarly, herbicidal use significantly reduced energy

Table 7.3 Energy equivalent of some popular herbicides use in India (Source: Green and McCulloch 1976; Audsley et al. 2009)

Sr. No.	Herbicides	Energy equivalent (MJ kg^{-1}a.i.)	Sr. No.	Herbicides	Energy equivalent (MJ kg^{-1}a.i.)
1.	2–4 D	107	8.	Linuron	310
2.	Atrazine	208	9.	Mesosulfuron-methyl	659
3.	Bromoxynil	302	10.	Metsulfuron-methyl	518
4.	Diquat	420	11.	Pendimethalin	421
5.	Glyphosate	474	12.	Simazine	226
6.	Isoproturon	378	13.	Trifluralin	171
7.	Iodosulfuron-methyl sodium	691	14.	Paraquat	460

demand in agriculture with a higher output/input ratio as reported by Franzluebbers and Francis (1995) and Deike et al. (2008) in maize, sorghum and other crops.

Herbicidal sequence, dose, time, and method of application affect the energy budgeting not only in terms of energy input but also energy output by enhancing herbicidal efficacy and crop yield in a cropping system. Herbicidal use now became an integral part of Indian agriculture due to scarce and costly labor availability. Manual weeding in wheat is energy-intensive practice and demand 4–5% higher input energy. Adopting less labor requiring approaches in weed management has great importance. Herbicidal efficacy improved the energy budgeting of crop production. Continuous use of a single herbicide in a particular cropping system is not so effective whereas mixing and sequential use of different herbicides broaden the spectrum of weed control. Tank mix application of pinoxaden, carfentrazon, and metsulfuron-methyl in wheat resulted in higher EUE, energy profitability and crop productivity in Haryana (Devi et al. 2018). Sequential application of pendimethalin followed by pyrithiobac-sodium in cotton required 4–8% less input energy than pendimethalin *fb* glyphosate directed spray and Pyrithiobac-sodium + quizalofop -p-ethyl *fb* directed spray of glyphosate (Rani et al. 2016). Application of adjuvant in herbicides enhance its efficacy and reduce the dose required; lower dose of the verdict (0.3 kg ai ha^{-1}) with bio-agent significantly enhanced the energy output and EUE in wheat (Zargar et al. 2016). Weed management strategies differ in energy use and its efficiency. Methods that suit best for effective weeds control with a higher yield of crops and cropping system significantly enhance the energy use efficiency. However, energy input of different herbicide did not vary much to the total energy input in crop, than methods and approaches of weed management. Continuous use of herbicide is not good for ecosystem health at all. Therefore, integrated use of herbicides with cultural, mechanical, and manual practices needs to be adopted for energy use also.

7.2.6 Energy Efficient Irrigation Techniques

India ranked highest among other countries on freshwater consumption; 80–90% of which are used for irrigation purposes in crops (Hoekstra and Chapagain 2007; Green et al. 2018; FAO 2016). About 160 Mha agricultural lands in India are covered by groundwater irrigation and 22 million by canals (Dhawan 2017). Irrigation has a direct role in energy demand. Largest proportion in-ground irrigation systems required huge energy quenching for pumping/extracting, distribution, and application. Current irrigation practices are consuming enormous water and their WUE are low (30–40%). For increase water use efficiency, scientific and modern techniques like micro-irrigation and crop management techniques also impose additional energy demand (Pinmental et al. 2004; Khan and Hanjra 2009). Seeking the present scenario, irrigation, and energy efficiency together needs to be improved through (1) efficient pumping techniques and (2) smart water use at the farm level.

7.2.6.1 Energy Efficient Pumping

India extracts about 230 billion m^3 of water every year for different purposes through pumping (Shah 2009) that impose direct energy demand in the form of fuel and electricity. The number of electric operated pumps in India is more than diesel operated therefore about 70% of groundwater extraction system uses the electricity (Mishra et al. 2018). Over an estimation pumping of 1000 cubic meter water from one-meter depth emitted 4–13 kg CO_2 (Karimi et al. 2012; Patle et al. 2016a, b) therefore groundwater extraction costs 222.38 billion m^3 CO_2 every year that contributed to global GHG emission (Mishra et al. 2018). It is therefore urgent need to adopt alternative strategies including use of nonrenewable energy sources like wind and solar energy as well as efficient pumping and water distribution techniques.

Energy requirement for irrigation and CO_2 emission together could be reduced by adopting renewable energy sources. India has a wide potential of solar energy of about five thousand trillion units annually (Muneer et al. 2005; Mukherjee and Sengupta 2020). Replacing diesel and electricity-based pumps with solar based could save huge nonrenewable energy. Though irrigation hours are limited (6–10 h in day time only) for solar-based pumping thus scheduling in the proper way matters (Picazo et al. 2018). However, the use of batteries in automated irrigation system suits best and reducing the nonrenewable energy uses.

Most of the Indian farmers on the one hand using nonstandardized, under and oversized electric pumps while on the other hand subsidized electricity to agriculture is provided by the government under its policies (BEE 2009). This resulted in overuse of electricity and other nonrenewable resources. Pump sets in India consuming about 25% of total electricity (Singh 2009). Energy efficiency could also be improved by avoiding under and oversized, inefficient local pumps (Tyagi and Joshi 2019). Use of efficient pumps and their timely maintenance could be able to save 30% (27.9 BU) electricity annually (NPC 2009). For the sake of this, several efforts have been made by the Government in times to provide financial assistance for replacing local pumps with BEE labeled pumps (BEE 2009). Further government is planning to reduce the energy consumption by 46 billion KWh power annually in the next few years by facilitating assistance to farmers for adopting energy efficient pump sets (WISE 2017). Proper maintenance of pump sets and pumping efficiency could save 40% energy use based on the current scenario (Tyagi and Joshi 2019).

After the ground irrigation, canals also contributed a major proportion of net irrigated area (23%) in India. Unlined canals and poor infrastructures at the farm level resulted in poor (38%) irrigation efficiency. Lining of canals, their maintenance, reducing water loss at farm gates and are able to reduce water loss (22.5%) thereby reducing energy use in agriculture (Arshad et al. 2009).

7.2.6.2 Smart Water Use Techniques

Surface irrigation method through flooding required a large amount of water. Water flows freely under the force of gravity and therefore gravity-fed irrigation system has negligible energy demand. However, over and uneven irrigation in flood and furrow methods reduces WUE. Drip and sprinkler method could replace gravity-fed irrigation and offer a significant reduction in water use (Playan and Mateos 2006; Zehnder et al. 2003). These highly pressurized irrigation systems consume much direct and nonrenewable energy; about 23–48% of the total energy of crop production used in pumping and operating the above said irrigation system (Singh et al. 2002; Khatri et al. 2013). Energy demand in the pressurized system depends upon the amount of water used by crop, depth of water table, flow rate, and efficiency (Lal 2004). Use of electricity and diesel as energy source directly contributed in carbon and ecological footprints. Pressurized irrigation systems produced 1.75 times more GHG (Patle et al. 2016a, b). For achieving better WUE along with lesser environmental impact, a smart balance between water use and energy consumption is needed.

Surface irrigation method is mostly practiced by the Indian farmers through pumping groundwater. In this method of irrigation water demand is high ultimately requires more time for pumping. Adopting laser land leveling and zero tillage in spite of conventional practices where gravity-fed irrigation systems are prominent, resulting in enhancing irrigation efficiency (70%) and reducing energy use by 15–20% (Naresh et al. 2016; Tyagi and Joshi 2017). Seeking future water demand and scarcity, shifting from pressurized free flow to micro-irrigation including sprinkler provides opportunity for efficient energy use. Micro-irrigation is able to save about 30% energy than traditional method due to overall reduction in water use (Tyagi and Joshi 2019). In spite of better WUE (70–75%), sprinkler system functioned under a high-pressure range of 98–294 kPa (Singh et al. 2009) and requires more energy for maintenance of pressure. This demand could be reduced by adopting low energy water application devices (LEWA). LEWA required lesser operating pressure (39–98 kPa) and facilitates a direct energy saving over pressured irrigation systems (Singh et al. 2010). Irrigation scheduling in rice under pressurized irrigation (sprinkler and LEWA) at two days intervals resulted in saving of 20–30% water use over surface method of irrigation. These twin systems required more nonrenewable energy but LEWA found 5% more efficient than sprinkler (Singh et al. 2016). The LEWA resulted in more energy productivity (1.64) followed by sprinkler (1.17) over surface (1.06) irrigation (Singh et al. 2018a). This difference is attributed to lesser fuel/electricity demand, amount of water used, and operating pressure. The amount of water use in crops also affects nutrient and energy use. Water guzzling crops required more water and nutrients thereby more energy`. This holds true in case of rice, sugarcane, and root crops. Water requirement of rice is more; intermittent and alternate wetting and drying in rice is a good practice in improving WUE and EUE (Tyson et al. 2012). Direct sowing and CA-based rice cultivation significantly reduced water, nutrients and energy demand (Jat et al. 2014). Similarly, sugar beet required more irrigation than bean and winter wheat therefore required 60 to 164% higher direct energy (Topak et al. 2005). Clearly, the efficient irrigation methods, irrigation scheduling, and the use of smart irrigation techniques not only reduces the energy demand but also reduces water wastage and increases nutrient use efficiency in crops.

7.2.7 Nutrient Management

The substantial growth in food production is achieved due to heavy use of fertilizers after the green revolution and ultimately leads to food security. Indian agriculture is consuming 265.91 LMT of fertilizers for the production of 2848.3 LMT foodgrains (GOI 2019). Scenario of fertilizers consumption is likely to increase which will require a huge amount of energy in its production process. It has been estimated that about 9.63–10.77 MTOE of energy will be required to meet increasing fertilizers demand by 2030 (BEE 2018). A large share in energy input is constituted by inorganic fertilizers in crop production (Nabavi-Pelesaraei et al. 2014; Singh and Benbi 2020). Therefore, achieving high fertilizers use efficiency with minimized energy consumption in crop production is the major challenge to be fulfilled now. Application of fertilizers in the right quantity at right time and advanced technologies could be helpful in improving resource use efficiency.

7.2.7.1 Amount of Fertilizer Use

Energy consumption in a cropping system varied with fertilizers use. It has a direct relationship; higher the fertilizer uses higher the input energy required. Nutrient management contributed 24–54% of total energy used in a cropping system (Amenumey and Capel 2013; Yadav et al. 2017; Singh et al. 2020c; Singh et al. 2019b). Crops require a huge quantity of N rates. Root crops generally need more input energy due to heavy fertilizers demand (Hulsbergen et al. 2002). Similarly, cotton required 7.3 and 14.2% less amount of fertilizers than maize and rice thereby reducing energy demand of about 6.9 and 12% along with more energy output/input ratio in Punjab (Singh and Benbi 2020). Most of the cereals and oilseeds demanded the huge amount of nitrogenous fertilizers. Indirect energy evaluation of different fertilizers indicated that urea formation is the high energy-requiring process. Higher nitrogen requirement of crops along with its higher energy equivalent (60.6 MJ kg^{-1} N) force to achieve better nitrogen and energy use efficiency at farm level (Esengun et al. 2007; Singh et al. 2019b).

Lower nutrient use efficiency is one of the reasons for higher fertilizer and energy use in Indian agriculture (Wassmann et al. 2009; Singh et al. 2020c). Balanced application of primary nutrients (NPK) in rice significantly raise the agronomical and physiological N use efficiency by 39.8% and 22.3% respectively, thereby higher net energy (6.03%) and energy productivity (8.0%) with 7.5% lesser GHG intensity (Singh et al. 2020c) over N application alone.

Rice seedlings in nurseries put additional fertilizers demand and energy. Direct seeding of rice required lesser N fertilizer (6–10%) application rate along with better use efficiency than conventional transplanting and was found efficient in terms of input energy (Mandal et al. 2015a, b). Fertilizers demand could be supplemented by FYM use. Reducing the N fertilizer dependency by 25% replacement through FYM in rice significantly enhance the energy output (87.6%) and productivity (102.5%) of yellow mustard grown in rice–mustard cropping sequence (Mallikarjun and Maity 2017). Higher energy productivity in sequential cropping is mainly attributed to lessen fertilizer demand by successive crops which is fulfilled by mineralized nitrogen. While, in situ residue covering resulted in higher fertilizer claim in main crops especially N. It is reported that soil surface covering in zero-tilled wheat put ~5% higher energy demand due to more nitrogen application rate needed by microbes during decomposition process (Singh et al. 2020c). Hulsbergen et al. (2002) advocated demand of much higher N fertilizer rates for better energy output than the amount required for maximum energy ratio and minimize intensity. Higher fertilization sustains the crop yield and food security of livelihood. It is almost impossible to minimize energy intensity in crop demand but a harmonious combination must be achieved.

7.2.7.2 Nutrient Source

Continuous intensifying GHG and energy needs due to fertilizers consumption along with the deterioration of soil health puzzled the agricultural researchers, farmers, and policymakers (Smith et al. 2004; Hoeppner et al. 2006; Rautaray et al. 2020). Rebuilding soil, water, and environmental health in agroecology is an opportunistic approach nowadays. Organic manure, green manuring, integrated nutrient management, use of bio-agents for nutrient fixation and remobilization curtailing fertilizers demand in several ways (Robertson 2015). Achieving nutrient use efficiency at farmer's field could save 32–38% total energy saving through various practices (Chauhan et al. 2006; Nabavi-Pelesaraei et al. 2014).

The INM helped in reducing energy input (24%) and improving energy efficiency (35%) over inorganic fertilizers (Rautaray et al. 2020). Integrated use of nitrogen in crop production not only enhance its use efficiency but also advocated to improve productivity, ecosystem health, and energy use efficiency. Farmyard manure is the easily available option to farmers for INM in India without much scientific knowledge but the high quantity is needed to replace the nutrient demand owing to less nutrient content (Dhar et al. 2017; Rautaray et al. 2020). Besides high C:N ratio, energy requirement for FYM application at the farm level in paddy is 60–65% of total crop energy demand (Ramchandra and Nagarathna 2001). Green manures in that condition may be feasible; it is reported that green manure had an annual potential of 14–15% primary nutrients saving (Rautaray et al. 2020). Use of sesbania green manure reduced 23.5% energy use in paddy over inorganic nutrient management. It substantially added 54 kg NPK ha^{-1} with only 317.5 MJ ha^{-1} energy use grown by using 20 kg seed ha^{-1} in situ before paddy cultivation (Rautaray et al. 2020). Additional application of FYM (10 t ha^{-1}) with inorganic fertilizers obviously enhanced the energy input as reported by Mandal et al. (2009) but 22.4% higher energy output and 20.8% net energy over NPK alone in soybean cultivation at Bhopal, India.

Energy efficacy could be realized by lessening the dependency on fertilizers nutrient through the use of organic manure and inclusion of legumes in a system (Metzidakis et al. 2008; Nabavi-Pelesaraei et al. 2014). Legume-based cropping system required relatively lesser nitrogen demand and hence energy use. Similarly, Yadav et al. (2017) reported least fertilizer energy demand (10,451 MJ ha^{-1}) in rice–legume cropping system than rice–toria and rice–maize cropping in rainfed area of India with better resource use efficiency.

7.2.7.3 Time of Fertilizer Application

Fertilizer manufacturing is energy-guzzling process. A unit quantity of nutrients production, packaging, and transportation consume direct and nonrenewable energy sources. Energy equivalent for fertilizers nutrients is 60.6, 11.1, 6.7, and 20.9 MJ kg^{-1} of N, P_2O_5, K_2O, $ZnSO_4$, respectively (Mobtaker et al. 2012; Unakitan et al. 2010; Pahlavan et al. 2011; Nabavi-Pelesaraei et al. 2014; Mandal et al. 2015a, b). Time of fertilizers application imposed negligible/low impact on energy input but affects its utilization during the crop production process (EUE). Higher nutrient use efficiency and crop yield likely to enhance the energy output and use efficiency (Yadav et al. 2017; Wassmann et al. 2009; Mandal et al. 2015a, b; Singh et al. 2020c). Synchronizing nutrient application especially N with crop demand, growth stage is key for improving N use efficiency (Giller et al. 2004; Singh et al. 2018b). It reduces fertilizer demand by eliminating nutrient loss from crop ecosystem (Pampolino et al. 2012). As indicated in earlier sections that diminishing nutrients demand through applying fertilizers at the right time of crop reduce the energy input and upshot output. Application of N fertilizers in more splits synchronizes its supply with crop demand. Phosphorus, potassium, and zinc at basal application are more helpful in improving crop yield vis-à-vis nutrient use efficiency. However, much research needs to be conducted to know the best time of nutrient application and its energy use pattern for achieving energy self-sufficiency.

7.2.7.4 New Approaches

It is reported that crops effectively utilizing only 17% of total N applied; rest costs the environmental problems (Erisman et al. 2008; Jat et al. 2012). This low NUE demanded more energy consumption with lesser EUE in agriculture (Shaviv 2005; Jat et al. 2012). Only 30–45% of recovery efficiency in major crops like rice, wheat, and maize was reported (Ladha et al. 2005). Therefore, researchers focused on many approaches like site-specific nutrient management, coated urea, leaf color chart (LCC), remote sensing and geographical, nano-fertilizers, slow-released, and coated fertilizers, etc. to improve NUE and declining its loss in the environment.

Inherent nutrient supply of soil never remains the same across the field. This large variability could be managed by applying nutrients as per soil testing and crop response calculations. This reduces the nutrient application rate and enhances its use efficiency. Various researchers reported 20–30% saving of nutrients following site-specific nutrient management approach with a higher nutrient recovery by crop (Gill et al. 2009; Khurana et al. 2008; Hach and Tan 2007; Jat et al. 2012). Leaf color guided nitrogen application through LCC or SPAD meter are able to save 12.5–25% fertilizer N over blanket recommendation (Bijay-Singh et al. 2002). Normalized Difference Vegetative Index (NDVI)-based N management is the most efficient approach for enhancing NUE (Gill et al. 2008; Gupta 2006). Controlled released and coated fertilizers reduced crop N requirement by 20–40% with higher NUE (Balkcom et al. 2003; Zvomuya et al. 2003). All these approaches are able to enhance NUE vis-à-vis reduced fertilizer application rate. Enhancing NUE is the most feasible way to reduce crop energy demand. Relationship of NUE with energy use pattern of major crops of India is shown in Fig. 7.5. It is advocated that

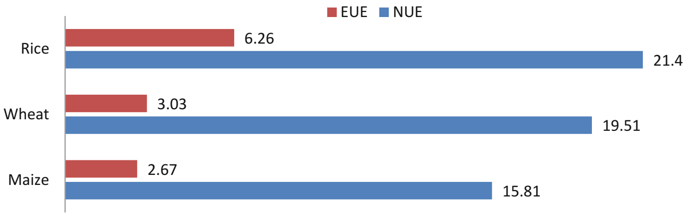

Fig. 7.5 Relationship of agronomic NUE of crops vis-à-vis Energy input and EUE (Source: Yousefi et al. 2015; Singh and Benbi 2020; Yadav et al. 2017)

enhancement of NUE resulted in better input energy utilization with greater EUE. Similarly, Yousefi et al. (2015) found a positive correlation with NUE and energy use efficiency. Though only few reports are available indicating energy use pattern of advanced nutrients management technology therefore, some researches are going on to curtail the energy demand in agriculture through efficient management technologies and its further demand in harvesting and postharvesting techniques.

7.2.8 Harvesting Techniques

Harvesting is the labor, cost, energy-consuming practice shared about 20–25% labor and total cost incurred in agriculture (Sahoo and Rehman 2020). Our agricultural system facing a huge shortage of labor and same time abnormal weather conditions like frequent rain and cyclones during harvesting, drying and threshing causes greater loss. Losses due to weather as well during manual harvesting operations along with high labor demand collectively responsible for inefficient energy use and efficiency in agricultural system. Canakci et al. (2005) reported high (9–22%) energy consumption in manual harvesting of maize, wheat and sesame due to high labor requirements. Mechanical harvesting and combining harvesting, threshing, and winnowing could reduce labor demand but at the same time increases energy use in agriculture. However, no doubt pressure of utilizing nonrenewable energy sources in agricultural system will enhance significantly the environmental costs due to CO_2 emissions. Therefore, renewable energy-based harvester and combiner needs to be developed.

Mechanization in agriculture solved many problems in agriculture but at the same time the Indian agriculture is currently facing challenges of nonrenewable energy crisis. Promotion of renewable energy use in agriculture needs to implement and is a need of time. Common machined-based harvesting operations consume a large amount of nonrenewable energy. Kiran et al. (2017) and Sahoo and Rehman (2020) advocated the use of electric-and battery-operated reaper with 35–60 cm cutting width in rice instead of diesel-based harvester. Average energy consumption of diesel-based combine harvester is 4500–6000 MJ ha^{-1} (Chaichan et al. 2014) which is much higher than labor-based (700–1100 MJ ha^{-1}) manual harvesting, threshing, and winnowing using more proportion of non-renewable energy (Yadav et al. 2017; Canakci et al. 2005). However, semi-automated solar-based mini paddy harvester is more efficient than conventional diesel based that completely relied on the renewable energy sources (Pathak et al. 2017). Therefore, seeking labor shortage in commercial farming, solar-based power reaper needs to be adopted which reduces dependency on non-renewable energy sources. This is also feasible for small and marginal farm land-holding farmers.

7.2.9 Postharvest Management

Postharvest management and value addition of crops beyond farm gate is an important agricultural practice. Globally, food production and supply chain consume about the world's 30% of total energy. Out of which, about 70% energy is consumed in postharvest processing, transportation, and value addition (FAO 2011; Vourdoubas and Dubois 2016). Postharvest losses of food have sizable proportion (30–35%) which imposed a great threat to most of food production, value addition and nonrenewable energy utilization. As far as pulses are concerned, postharvest losses are to the tune of 25–50% (Birewar 1984; Jeswani and Baldev 1990; Pratap et al. 2016); and most of losses are during value addition (15–20% in milling) and improper storage (5–10%). Though postharvest value addition itself is the big concern in energy use and management.

The foremost postharvest operation after threshing is the drying of grains to obtain proper moisture content. Rice, generally, harvested and threshed at 20–25% moisture but it needs 12–14% grain moisture content for safe storage (Van-Hung et al. 2016; Gummert et al. 2020). An average traditional dryer consumes about 4–6 MJ of energy for kg^{-1} grain; sun drying is the least nonrenewable energy-consuming practice but need more space, time, and human labor (Jittanit et al. 2010; Sims et al. 2015). In rice processing and milling, parboiling process requires huge amount of thermal energy whereas the traditional parboiling process needs 240 to 1600 MJ t^{-1} thermal energy (Ahiduzzaman and Islam 2009). Modern rice milling processes are less energy consuming but need nonrenewable energy (105 MJ t^{-1}) in the form of electricity (Ahiduzzaman and Islam 2009). Out of total electricity consumed in rice milling in India (Fig. 7.6); 82% shared by drying and milling process and 4% by parboiling (Sims et al. 2015).

Energy quenching in postharvest processing and management is a diverse challenging situation. High energy requirement owing to improved and modernized processing and milling processes over farmers practice; but energy output may be higher. Gummert et al. (2020) reported more energy output (34.44 GJ ha^{-1}) and input (16.88 GJ ha^{-1}) in improved postharvest processing and milling using a combine harvester, flatbed dryer, and hermetic storage (IPR) over farmer's practice. However, energy use efficiency is reported higher (2.04) in IPR owing to lesser harvesting loss (3–7%) due to grain loss in shattering, grain damage and labor demand over farmer's practice (1.95). Efficient processing techniques save 30–35% losses during value addition and are able to upshot efficient energy utilization in food-supply chain.

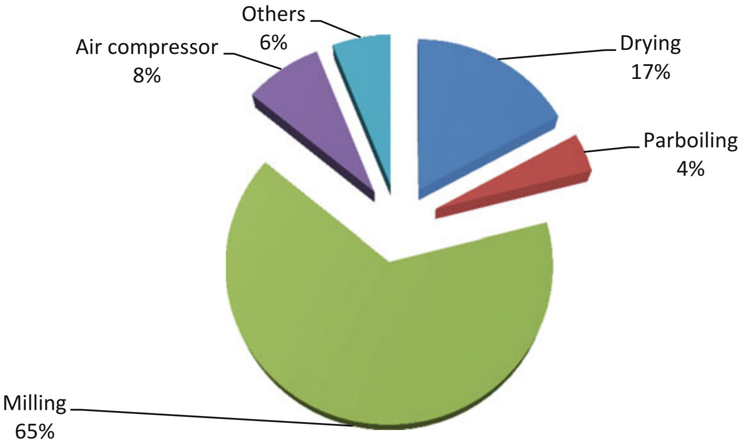

Fig. 7.6 Proportion of electricity used in various practices of rice milling in India (Source: REEEP 2010; Sims et al. 2015)

7.3 Protected Cultivation and Energy Use Pattern

Protected cultivation in India covers about 1.5 lakh ha of area, out of which 20% comes under greenhouses (NHB 2017). Protected cultivation alters micro-climate of crops partial/fully that facilitate and accelerate the crop productivity. Alteration in microclimate consumes 2.5 times higher input energy compared to open field (Pandey et al. 2020). Energy utilization pattern in greenhouses differ. Most of the input energy in greenhouse is required for crop protection measures (28.9–55.7%), while in open field more energy is consumed in tillage and soil management.

Electricity is the main source of direct energy supply for maintaining temperature, humidity, and irrigation. Share of electricity in some greenhouses may be higher due to heavy use in heating and drip irrigation systems (Kuswardhani et al. 2013). However, fertilizers energy input is more or less equal in both the conditions (Hedau et al. 2013); plant stacking, training, and pruning consumed the bulk of energy (16.3–21.9%) in greenhouses. According to Djevic and Dimitrijevic (2009) fertilizer is the third-largest energy input practice, after energy consumption for heating and that embodied in boxes. In general, fertilizers shared 21–27% energy input source for tomato, chili, and lettuce production in greenhouses (Kuswardhani et al. 2013) and uses more direct energy. Ozkan et al. (2007) reported 60% share of direct energy in greenhouse grape production in Turkey with lesser nonrenewable energy (81.30%) in greenhouse than open field (93.16%). Greenhouses use electricity as direct energy sources for maintenance of temperature to some extent, humidity and light depending upon its type, crop, and management. Under certain climatic condition and cropping pattern electricity used for heating or cooling contributed about 60–80% of total energy consumption (Gruda et al. 2009; Gruda and Tanny

Table 7.4 Potential energy conservation techniques in green/poly houses (Source: Gruda and Tanny 2014)

S. no.	Type of saving	Saving potential (%)
1.	Thermal screen	20–40
2.	Sealing of vents and windows	10–20
3.	Heating system	10–18
4.	Optimization of boiler	10–15
5.	Climate control	10–20
6.	Better use of cultivation area/crop planning	10
7.	Special insulation and glazing	7–10
8.	Sensors	5–10
9.	Irrigation	5–10
10.	CO_2-fertilization	5

2014). Greenhouse development and installation itself consumes huge energy; about 400–500 MJ m^{-2} ground area energy embodied for typical greenhouse construction (Canakci and Akinci 2006). This puts additional burden on energy demand.

Pandey et al. (2020) reported 64% higher output/input energy ratio and energy productivity (62.5%) in poly-house cucumber production over open land. Similarly, Kuswardhani et al. (2013) reported energy ratio of 0.85, 0.45, and 0.49 in greenhouse production which is much higher than open field vegetable production (0.52, 0.17, and 0.18) for tomato, medium land chili, and highland chili, respectively. Crop cultivation in greenhouses, plastic mulches, poly houses, tunnels efficiently utilize solar energy. Broadly speaking, solar energy is the main source (65%) in terms of benefits for greenhouses. Besides its high energy consumption, EUE in greenhouse is always high. Elings et al. (2005) further suggested some important measure for improved total energy utilization and efficiency in greenhouse production. Increased insulation had potential of 23% energy saving while lowering temperature set point had 16% saving potential. Some practices like elevated relative humidity, screen gap control, and temperature integration had saving potential of about 5%. Some other practices are able to reduce energy consumption in green/poly houses that are listed in Table 7.4.

7.4 Alternative Land Use Management

About one fourth (205 million acres) of India's geographical area is under community forest, pastures, and water bodies. These serve as vital ecological functions, global energy balance and, contribute to carbon sequestration, biodiversity conservation, hydrological supplies and have social, cultural significance to rural communities. They further engage the critical livelihood requirements of more than 350 million of India's rural population (Dhyani et al. 2013). Alternate land-use systems, technologies and agroforestry include planting woody perennials (trees, shrubs, palms, bamboos, etc.) on the same land-management units with agricultural crops and/or animals, in any sort of spatial or temporal sequence. In agroforestry systems, both ecological and economical interactions between the different components prevailed (Kavargiris et al. 2009). Nutrient cycling is much more efficient in agroforestry than any other agricultural systems due to presence of woody perennials. It includes endless alteration of nutrients within different components of the ecosystem and involves processes, such as weathering of minerals, activities of soil microfauna and flora. The conversions occurring in the biosphere, atmosphere, lithosphere, and hydrosphere also include in nutrient cycling (Michos et al. 2017, 2018). In agroforestry, more nutrients in the system are reused by plants (compared to agricultural systems) before being lost from the system. The two significant differences between agroforestry and other land-use systems are (a) the transfer or turnover of nutrients within the system from one component to the other; (b) the feasibility of maintaining the system or its components to promote increased rates of turnover without influencing the overall productivity of the system. The input demand in agroforestry is less with better efficiency; therefore, consumption of nonrenewable energy and greenhouse gas emissions are also lower (Platis et al. 2019).

Higher productivity along with lesser nutrient demand due to efficient cycling and integrated biological cycles made agroforestry less energy consuming practice. Lin et al. (2013) reported the better energy balance of agricultural subsystem, forestry subsystem, and agroforestry system as shown in Table 7.5. Forestry subsystem and agroforestry system had higher EUE (23.0 and 12.8, respectively) than some of the other agricultural subsystem viz. potato and wheat. The lower EUE of agroforestry system might be due to lesser yield in comparison to forestry system. Jianbo (2006) reported 9.45% higher EUE of Paulownia-based wheat–peanut intercropping than traditional non-agro-forestry cropping system (wheat–peanut). Similarly, Pragya

Table 7.5 Energy balance of agricultural subsystem, forestry subsystem, and agroforestry system (Source: Lin et al. 2013)

	Input energy (GJ ha^{-1})			Yield (Mg-DM ha^{-1})	Energy output (GJ ha^{-1})	EUE
	Direct	Indirect	Total			
1. Agricultural subsystem						
Potato	5.0	5.2	10.2	6.0	104.0	10.2
Wheat	3.3	1.4	4.7	2.5	46.0	9.7
Sunflower	3.7	1.7	5.4	2.6	70.0	13.0
Crop rotation	3.0	1.8	4.8	2.5	47.9	10.0
2. Forestry subsystem						
Forestry	2.5	2.4	4.9	5.4	111.3	23.0
Poplar				6.4	128.7	
Willow				4.0	75.4	
Alder				4.7	88.7	
Black locust				6.6	152.6	
3. Agroforestry	2.9	1.9	4.8	4.8	61.6	12.8

et al. (2017) advocated better net energy ratio of agroforestry-based biofuels system (4.2–6.44) over soybean-and corn-based cropping system (0.88–1.35).

Agroforestry system could minimize nonrenewable energy inputs in agricultural production and reduce GHG emission (like CO_2, CH_4, N_2O, etc.). On the other hand, it also increases EUE of crop production along with vegetative carbon and soil organic carbon stocks of the soil. Renowned scientist and research analyst during conference of parties (COP21), i.e., Paris agreement suggested agroforestry as a measure in adapting the ill consequences of climate change and reducing GHG (Baah-Acheamfour et al. 2017). Agro-forestry ecosystems, such as intercropping with best management practices, could enhance both EUE of the production system and the added-value of the agricultural products.

7.5 Efficient Livestock Production and Management

Global chain of livestock production and management provides services to 1.3 billion people and contributed 40% of the value of agricultural output (FAO 2009; Rota 2012). India has about 512 million livestock; mainly buffalo (37%), goats (26%), and Cattle (21%). Livestock is the integral part of agriculture which acts as both source and sinks for the energy. Mostly dairy animals, buffalos, cows, and crossbreeds of cattle are integrated with agriculture and are gaining popularity. Livestock consumes energy in terms of green fodder, feed, and concentrates. Daily energy requirement of cattle is 17–33 GJ per unit; but the crossbreeds require highest among other breeds (Saini et al. 1998). Energy intake for feed depends upon the daily feed intake and body size; buffalo has more bodyweight therefore required more energy. However, some crossbreeds of cows like Jersey, Holstein Friesians, etc. also required similar energy intake.

Despite higher energy demand of crossbreeds of cow and buffalo, energy output of buffalo, in general, is higher than cross-breeds of cow. Indian local cow (*desi*) yielded very less milk owing to low-energy output (12 GJ day^{-1} unit^{-1}). Energy output of buffalo and crossbreeds of cow ranged 45 to 50 GJ day^{-1}. Howbeit energy use efficiency is more in the case of crossbreed cow due to higher milk yield with lesser feed requirement. Manures of cattle and buffalo serve as energy for humans and crops-nutrient sources in rural India. Livestock production and their waste have great potential for renewable energy sources. Crop waste is mainly straw used for feeding material for livestock and manures used as nutrient sources for crop; a synergism in crop-livestock system prevails. Integrated farming system model comprising crop with mushroom, poultry and goat rearing consumes about 2.98 GJ and 24.53 GJ direct and indirect energy, respectively for one acre land in Bihar; highest proportion used by goatry (Kumar et al. 2019). Integration of livestock with agriculture enhances the energy use in agricultural system. Woods et al. (2010) reported more energy use efficiency (0.11–0.5) in integrated cultivation with crop over isolated rearing of poultry and animal husbandry (0.7–1.7). Therefore, integrated farming system were found more efficient in terms of energy productivity and utilization.

Livestock waste in general is used as energy source by combusting in India; dried cow-dung cake has a calorific value of 14 MJ kg^{-1} (Kaur et al. 2017). About 60 million tons cow-dung used as a direct energy source in India. Direct combusting of cow-dung produces a huge amount of CO_2 and is a concern for major environmental issues. Cow-dung has much potential for biogas production—a direct energy source. Biogas contains 60–70% methane which could be used for direct combusting in kitchen or electricity production (Chasnyk et al. 2015; Sun et al. 2015). Biogas contains 16–25 MJ m^{-3} energy equivalents and could produce 5–7 kWh m^{-3} electricity (Kaur et al. 2017). Indian cattle waste had a potential of 263,702 million m^3 of biogas generation along with 477 TWh of electrical energy. The increasing demand for both direct and indirect energy in different sectors of agricultural systems need to be managed through the efficient use of these energy sources at the farm level. In this context, various policies or strategies need to be enacted by lawmakers and stakeholders in contribution with various institutional supports for the sake of the environment, human welfare, and ecological safety. Some of the laws and policies are already undertaken by the government of India to split the energy demand in each demanding sectors.

7.6 Policy and Institutional Support

Agricultural production demands about 203 BU approximately 18% of total available energy in India (BEE 2019). The foregoing data about demands of energy consumption globally as well as in India showed marked effects of rapid growth in energy demand and carbon footprints. Continuous power supply results in carbon emissions and is not cost-efficient. On the other hand, rely on renewable energy for pumping and irrigation can make the situation better and ultimately reduce GHG emissions and are cost-effective for large-and small-scale farmers. Electrification without decarbonization is the main slogan in developed and developing countries. But to decarbonize the power sector in agriculture, each country should utterly develop awareness on efficient strategies and sustainable approaches that offset the growth of carbon footprints. Some important approaches have been undertaken by the government of India to ensure reduced augmentation in CO_2 emissions and to split the energy demand of each sector in a sustainable manner are as follows;

- Shift toward the use of renewable energies in an efficient way.
- Formation of innovative policy measures in coordination with private institutions already working in that path.
- To increase the access of energy technologies and practices.
- Policies for energy-smart food production.
- Increase in output per unit of energy use.
- Technological change in energy efficient farm machinery and irrigation system.
- Reduction in petroleum as well as fertilizer consumptions.

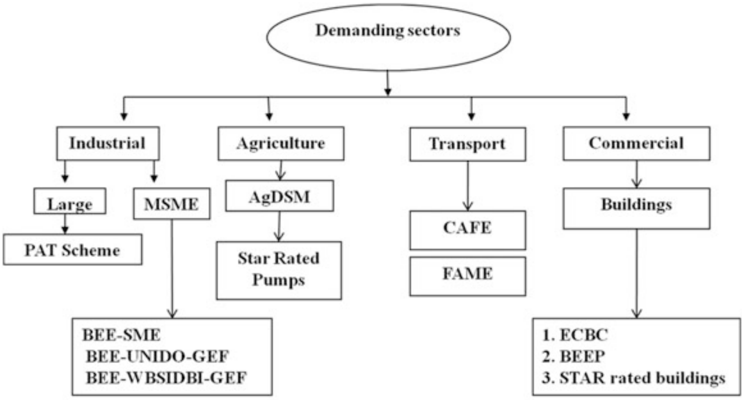

Fig. 7.7 Energy efficiency schemes in demanding sectors

Broadly speaking, each service sector indirectly contributes a fine share in energy consumption for agriculture sector. So, importance was given by the government of India to agriculture sector and several steps were taken to combat the energy consumption in a sustainable manner. The approach to promote technologies, institutions, and policy measures for alternative renewable sources of energy is a win–win approach for small-and largescale farmers. To monitor, review progress, and enforcing the implementation of energy policies availability of good quality and timely energy data are important.

Bureau of Energy Efficiency (BEE) initiated many national, state, and sector levels energy efficiency programs in coordination with several agencies and institutions that ultimately results in crosscutting the trend of India's energy consumption of the economy. The Fig. 7.7 represents prominent schemes in different demanding sectors (BPSRWE 2019). The estimated overall energy savings of about 23.728 MTOE in the year 2018–2019 was observed with the adoption of the aforesaid energy efficiency schemes. The PAT scheme saves 7.064 BU of electricity energy and together with other energy savings resulted in 25.529 Mt. CO_2 emission reductions. The agriculture sector (including Star Rated pumps) accounts for 7.051 BU of electrical savings. The overall total energy saving in this sector was 0.61 MTOE that also results in 5.78 Tone of CO_2 year^{-1} reduction emissions. Whereas, Corporate Average Fuel Economy (CAFE) and FAME schemes accounts for 0.848 and 0.038 MTOE of total energy savings with reduced emissions to the account of 2.650 and 0.070 Mt. CO_2 in 2018–19 (BPSRWE 2019). As far as the commercial sector is concerned which also includes farm infrastructure and buildings STAR-rated buildings and other Green Building Programme accounts for total savings of 0.007 and 0.006 MTOE and reduction in emissions to the tune of 0.068 and 0.057 Mt. CO_2 respectively. in the year 2018–2019.

Since, we are discussing agriculture sector as our major concern we will continue with the major policies undertaken under this sector. Agriculture to industrial sectors encompasses growth in power demand. Two approaches in these sectors mainly focus on first, gradual shift toward Renewable Energy (RE) and second, integration into the grid and systems approach on engendering Energy Efficiency (EE) practices. The amended Energy Conservation Act in 2010 directed its policies to focus specifically on energy efficiency programs and schemes like by setting of BEE and National Mission for Enhanced Energy Efficiency (NMEEE). Besides BEE doing commendable jobs in energy efficiency, initiatives were also proposed to other organizations, such as EESL, SIDBI, PCRA, SDAs, etc. EESL stakeholders take initiatives on SLNP, UJALA, BEEP, AgDSM, National EV Mission schemes, SIDBI worked on BEE-WB-GEF, PRSF schemes, PCRA organization is involved in Fuel Efficiency Programme, whereas TERI involved in GRIHA Rating System and so on.

7.6.1 National Action Plan on Climate Change (NAPCC)

The plan was enacted in 2008 and released by the government of India, and the main objectives of the plan were to combat energy consumption and related carbon emissions. National Mission on Enhanced Energy Efficiency (NMEEE) was one of the parts of NAPCC having four initiatives

- Perform Achieve and Trade (PAT),
- Market Transformation for Energy Efficiency (MTEE),
- Energy Efficiency Financing Platform (EEFP).
- Framework for Energy Efficient Economic Development (FEEED).

Among these, PAT is related to energy demand reduction of fertilizer sector also (BEE 2018). This is the one of the important program for large-scale industries mainly targeted to reduce their Specific Energy Consumption (SEC) over a period of 3 years. The fertilizer industries that maintain their Specific Energy Consumption would be issued Energy Saving Certificates (ESCerts) and those industries who could not achieve the target have to either pay penalties or have to buy ESCerts. The energy savings under fertilizer production was to the tune of 0.78 MTOE with reduction in CO_2 Emissions by 0.93 Mt. CO_2 year^{-1}. So far, the fuel-saving in fertilizer production is concerned about 2.0% of electricity saving and 90.0% of gas-saving was observed. PAT Cycle-I started in 2012 to 2015 whereas PAT Cycle-II started in 2016 to 2019. These cycles were formed to identify "Designated Consumers" (DCs) in cycle-1 and to identify new DCs in existing sectors in cycle-2.

7.6.2 Energy Saving Through Micro-Irrigation

The government of India undertaken to formulate a task force on micro-irrigation in 2004 to enhance saving of water use along energy through adoption of micro-irrigation. National mission on micro-irrigation (NMMI) is successful in 30% saving of direct energy consumption by covering >7Mha additional land under micro-irrigation (Global AgriSystem 2017).

7.6.3 Efficient Pumping Techniques

Indian farmer's using inefficient local pumps for groundwater extraction at their farm. The government made efforts to replace these with high energy efficient BEE labeled pumps (Tyagi and Joshi 2019; BEE 2009). This has about 40% total electricity saving potential (Patle 2016a, b) with average 40–50% energy efficiency of labeled pumps compared to non-BEE labeled pumps (25–30%). To combat the problem, the government of India has launched AgDSM programme. About 5109 to 63,615 BEE five-star rated 5 HP pumps were installed from 2016 to 2019 that ultimately results in saving of 0.18 BU electricity and 0.148 million ton reductions in the emission of CO_2.

7.6.4 Policies for Improved Water and Energy Efficiencies

To promote climate-resilient agriculture government of India had put forward some other programme like:

- National Innovations on Climate-Resilient Agriculture (NICRA) in 2011 (ICAR 2011).
- Accelerated Irrigation Benefits Program (AIBP),
- Pradhan Mantri Krishi Sinchai Yojana (PMKSY),
- Rashtriya Krishi Vikas Yojana (RKVY),
- National Mission on Micro-Irrigation (NMMI), or promoting water-use efficiency (GOI 2017).

7.7 Conclusions

Besides foodgrain self-sufficiency, higher use of mechanization, fertilizers, irrigation, and changed cropping patterns drastically enhanced the energy consumption in Indian and global agriculture. Changing global climatic scenarios and energy demand is serious threat for sustainable green future. Energy demand of India stands third after China and the USA; where agriculture consumes about 5% (29,311 MTOE) of total direct and indirect available energy sources. Tillage (10–30%), fertilizers (24–50%) and irrigation are mainly energy-intensive agricultural practices. Highest proportion of direct energy consumption attains by electricity used in agriculture. Since, we are on verge of energy crisis, achieving energy efficiency in agricultural practices are win–win strategy. Diversified and legume-based cropping is most energy-efficient cropping pattern. CA-based tillage including zero-or reduced tillage with residue covering could reduce 50–70% fossil fuel demand with better EUE and productivity. Problem of 37 Mt. CO_2 emissions in environment from residue burning in India could also be solved by in situ residue management. Achieving higher WUE along with reduced energy demand are major challenges in India. LEWA and drip irrigation is prominent technology of many field and horticultural crops. Weed management shares very less (2–5%) in energy consumption pattern. Herbicides bypass the indirect energy demand of labor. Crop rotation with legumes, INM, site-specific nutrient management with advanced technology reduces demand of fertilizers. Effort for enhancing NUE through modern approaches indirectly upshot the EUE. Renewable energy-based machineries like harvester, dryer, and milling could reduce 10–15% energy used in agriculture. Protected cultivation using greenhouses efficiently harness renewable energy sources, i.e., solar energy. Integrated farming and agroforestry-based land-use management with animal components are the best energy efficient practices which need to be adopted now for sustainable green future.

7.8 Future Prospectus

As per the present growth rate, we are on verge of an energy crisis; triple energy will be required for sustaining food security by 2040. Indian agriculture mainly uses subsidized electricity and fossil fuel which are energy inefficient and a threat for green future. Reducing nonrenewable energy demand in agriculture is the talk of the town and challenges researchers, policymakers and farmers. Reducing direct energy consumption and promoting renewable energy in agriculture through policies and institutional support must be undertaken. Energy and food security are twin challenges in agriculture. Our efforts should be energy-oriented; only reducing energy demand is not a solution as food security might be on a threat. Our goals should be enhancing EUE rather than reducing energy consumption. However; many agricultural practices are able to reduce energy demand by enhancing input use efficiency but more needs to be evaluated. Energy budgeting of many modern technologies for higher NUE and WUE is still lagging behind. Most of the researchers focus on curtailing direct energy demand while indirect energy must also be curtailed down. Obviously, modern tools and implements are effective in equilibrated use of natural resources; but information on their energetic are meager. Our green future will depend upon energy availability and climate scenario. Reducing GHG emission by better energy use pattern is need of hours.

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Carbon Farming: For Climate-Smart Agriculture and Environmental Security

8

Nilam Kondvilkar and Ritu Thakare

Abstract

Carbon (C) farming includes practices that are considered to raise the rate at which CO_2 from the atmosphere is removed and transformed from plants and soil into organic matter. C farming is successful, where C benefits arising from better land use or restoration practices outweigh C losses. The 2018 report by the Intergovernmental Panel on Climate Change, clearly indicated that transition is required to limit the impact of climate change to 1.5 °C Celsius increase in global temperature. This will require that 570 gigatons of carbon dioxide remain within the accumulated carbon budget, to reach about no carbon dioxide emissions globally around 2050, limiting the effects of climate change to 1.5 °C will require significant improvements in agriculture to how we manage our forests and natural carbon sinks. C farming may provide landholders with financial support to reduce C emissions, but it should still stand to achieve several co-benefits, both economic and environmental. Population expansion across the globe has led agriculture to be a major mode of global soil management. Because of the rapid increase in population and growing food needs, human impact on the soil is accelerating. Humans involved land-use practices and land-use or land-cover alterations caused differences to the natural fluxes that were superimposed. Land-cover shifts, expressed in surface albedo and hence exchanges found in surface-atmosphere energy and these are also regulating for surface and vegetation changes that have an adverse effect on regional level climatic conditions. Terrestrial habitats are major C sinks and sources, and so changes that occurred in land-use pattern are often reflected in the C cycle. Among the economic sectors that produce GHGs and thereby lead to climate change, agriculture is exceptional.

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Indeed, agricultural operations lead not only to origins but also to major CO_2 sinks. 13.5% of worldwide GHGs emission are compensated for by agriculture's exposure to GHGs. The minimal tillage of soil is one method that used in C farming for regenerative agriculture campaigns. Tillage elimination can be a major part of the response to the adversely changing climate crisis. Soil is a most dynamic natural C reservoir, potentially containing up to three times the atmosphere's C content. Other activities in C smart farming require planting of shelter. In addition, the government needs to boost energy production, avoid the destruction of trees, speed up the production of low-emission technologies, produce versatile fuels, substitute low-C coal with low-C gas, increase plantation areas for C capture and storage, etc.

Keywords

Carbon farming · Sustainable environmental security · Climate change · Food productivity

Abbreviations

BPO	Business process outsourcing
C	Carbon
CAT	Climate action tracker
CDM	Clean development mechanism
CH_4	Methane
CO_2	Carbon dioxide
CS	Carbon sequestration
EEA	European Environment Agency
FAO	Food and Agriculture Organization
GDP	Gross domestic product
GHG	Green house gases
HS	Humic substances
INCCA	Indian Network for Climate Change Assessment
IPCC	Intergovernmental Panel on Climate Change
Pg	Peta gram
SOC	Soil organic carbon
SOM	Soil organic matter
UNEP	United Nations Environment Programme
US-EPA	United States Environmental Protection Agency
RT	Reduced tillage
NT	No-tillage
DDT	Dichloro diphenyl trichloroethane
NAPCC	National Action Plan on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change
Gt	Giga ton

CC	Climate change
CE	Carbon emission
GR	Green revolution
N	Nitrogen
CTA-CCAFS	Technical Centre for Agricultural and Rural Cooperation and Research Program on Climate Change, Agriculture, and Food Security
EU-ETS	European Emission Trading System
COVID-19	Coronavirus diseases-2019

8.1 Introduction

Food, services, and energy are provided by agriculture and the survival of millions of people worldwide is assured. Agriculture is one of the most climate-dependent socioeconomic sectors in the whole world, since most of the productivity and efficiency of agriculture depend directly on various climatic factors (McArthur 2016). Agriculture is now influenced by climate change, with unevenly dispersed impacts across different parts of the world and throughout Europe. (IPCC 2014, 2018a, b, 2019; EEA 2017, 2018; Ciscar et al. 2018).

For climate change to affect agriculture is extremely vulnerable and there is a need to adapt to different changing climatic conditions. Climate change will decrease crop yields by 10% to 20% under ambitious estimates of lower end temperature increases (Jones and Thornton 2009), whereas droughts and floods are on the increase and can cause sudden food crop prices to rise by 2050. Climate change would also have an effect on agriculture through its impact on various processes. There are dynamic connections between habitats and climate change, and the overall effect on production and food security is rather unclear (Gornall et al. 2010; Kumar et al. 2018).

The continuous change in crops lands, forestry, and land-use account for nearly 25% of anthropic emissions of GHGs largely through deforestation, animal emissions, surface disruptions, and soil fertility management on an intensive basis (Smith et al. 2014). Worldwide total GHG emissions are similarly distinct from 8% to 18% of global anthropogenic emissions from near about 17 billion domestic animals. (Gerber et al. 2013; US-EPA 2012; O'Mara 2011). The principal origins of GHGs are the methane of enteric fermentation from ruminants and fertilizer, N_2O from manures and organic manures slurry, and CO_2 emits from different sectors of agriculture (Gerber et al. 2013). Total non-CO_2 emissions from the agriculture sector are projected to be 0.2–5.8 Pg CO_2 equivalent $yr.^{-1}$ (Tubiello et al. 2013a, b; FAOSTAT 2016) which is reflecting about 10–12% of total anthropogenic GHG emissions. Around 1990 and 2010, agricultural non-CO_2 emissions rise by 0.9% $yr.^{-1}$, with a significantly lowered down rate of increase after the year 2005 suggested by Tubiello et al. (2013a, b). The 70% of overall Non-CO_2 emissions reflect into field soils, followed by production of paddy rice, (9–11%), biomass (6–12%), and combustion and control of the mixture (7–8%). Enteric fermentation accounted for more than 40% of the total emissions from the global agricultural sector and more than 70% of methane emissions, and enteric fermentation is the major cause of total GHG emissions in 2014 from global agricultural sectors. The principal origins of GHG are the CH_4 of enteric fermentation and fertilizer, the N_2O of manure and organic manure slurry and the CO_2 of land-use trends.

India's per capita GHG emissions were 2.7 t CO_2e in the year of 2015 and it is around seventh in the emissions of the US and less than half of the world average emission of 7.0 t CO_2. Another target is to consume 2500--3000 Mt. of CO_2 by new woodland and vegetative cover by 2030. In the view of CAT, more than half of this sustainable goal could be reached by the Green India Project, launched in 2014, which aims to extend tree cover by 5 m hectares and improve the efficiency of another 5 m hectares of existing vegetative cover over 10 years. The Government of India also provides more incentives for state action to improve forest areas by relating it to funding allocations. Due to the primacy of food protection, any alleviation programmes in the agriculture-based industry must concentrate on reduction in GHGs emissions instead of aggregate GHGS emissions. Focus on lowering the rate of emissions requires a mix of environmental and humanitarian agendas since many of the conservation opportunities in the agriculture and allied sectors are fully correlated to sustainable productivity and returns. There is a significant and mainly unmet opportunity for investment in agro-based systems to decrease GHG emissions and to improve the overall stability of the agriculture and allied sector by facing climate change impacts while preserving and maintaining them. We assume that the mitigation agenda, which does not minimize these other priorities, should not only be adopted and properly executed, but also, that it is in the best long-term interest of different stakeholders across the different agro-based and allied sector, including central governments, agribusiness, multi-or bilateral financial institutions and, in particular, farmers. That said, deciding when and how best to achieve GHG emission reductions and C farming would depend on the particular agricultural systems, as well as specific political and economic conditions for the country and region. Therefore, it is important to consider, reconcile, and maintain trading between potentially conflicting priorities for the agro-based and allied sectors (Kumar et al. 2020; Meena et al. 2020).

From a natural resource viewpoint, modern industrial agriculture development and food systems are unsustainable which can lead soil erosion, nitrogen shortages, and habitat destruction, lead to a decline of water quality and water depletion, and eventually contribute to GHG and air pollutant emissions, which in turn contribute to climate change (UNEP 2016). At the same time, the agricultural industry offers C storage opportunities on the basis of management activities (e.g., by means of cover-cropping, tillage conservation, rotational grazing) and environmental factors (e.g., by cover-cropping, tillage conservation, rotational grazing) (Zomer et al. 2017).

Emission reductions and improved resistance to climate change allow for new alternatives to farming activities. C farming aims to increase productivity in a sustainable manner, improve the resilience of farmers and reduce the contribution of agriculture to changing climate by reducing GHG emissions and enhancing the storage of C (Campbell et al. 2014; Kumar et al. 2021). C Farming on a sustainable basis requires all practices that enable farmers to maximize their benefits; like social and economical of land while preserving and enhancing the environmental services offered by different land use. Sustainable management practices is replaced by conventional practices related to high GHG soil emissions. Terrestrial C sequestration is a process that biologically consumes photosynthesis of atmospheric CO_2 and retains it like C in sinks, such as biomass and soil. It involves the rejuvenation of absent C and the addition of fresh C above the initial stages as organic inputs. Traditionally, farmland has emitted 60–80 Pg C every year (Lal 2001).

New C restoration techniques, e.g., deep-rooted annual and perennial crops and pasture grasses will increase the equilibrium of the original soil C. the agricultural soils have a great potential to sequestered the more C by the incorporation of crop residues, such as mulch, intercropping, growing agroforestry, and integrated nutrient and water management. A number of other activities can also increase the storage of soil C, including: improved management of crop residues, expanded crop rotations, planting cover for crops and seasonal crops, control of soil erosion, improved management of soil moisture and nutrients, and high use of cultivation systems involving limited tillage or No-Tillage (NT) and reduced tillage (Lal 2004a, b; Yadav et al. 2020).

In other way, environmental factors adjust the amount of C deposition in the soil or its rate of decomposition. Farmers will raise yields, mitigate poverty in rural areas, decrease emissions of GHGs and counter the effects of changing climate on agricultural ecosystems through the introduction of C-growing practices to increasing soil C. These activities favor the aggregation of C across several systems. The management practices like improved fire control and tailored grazing power and pacing would increase the C stock of grassland.

The aim of this chapter is to identify the mitigation measures for climate change concerning agriculture through the implementation of large-scale agricultural techniques of C storage, C sequestration processes, and technical options in different terrestrial C reservoirs, with a view to reduce the rate of increase in atmospheric CO_2 concentration, with special reference to agriculture and soils of pasture or grasslands. This chapter examines the detailed amalgam and integration and information on the effect of the numerous C farming activities on soil C sequestration rates and their direct and indirect impact on environmental quality under changing climate scenarios.

8.2 Concept of C Farming

C farming is one of the major processes of changing traditional agricultural practices or land-use systems to increase the C sequestration in agricultural soil and vegetation and to reduce GHG emissions from the sources. C farming potentially offers to all farmer’s financial incentives to reduce C pollution, but should always aim to achieve multiple economic and environmental co-benefits (Cho 2018).

In order to improve the storage of C content in the agricultural soil and plants and to minimize GHG emissions from animals, soil, or vegetation, C farming is the important and needful process of modifying traditional farming practices or land-use systems. (Curnow 2020).

Agriculture‘s solution to climate change is C farming. Simply stated, the aim is to remove excess C from the atmosphere, where the factor induces global warming, and store it in the soil, where the growth of plants is supported by carbon. The theory is very straightforward-the reality, not so much. It is essential to manage the emission from land, water, plant, and animal resources to meet the triple challenge of degraded landscape restoration, global climate change, and food security.

C Farming can range from a single shift in a single technology of land management, such as the implementation of no-till agriculture or grazing management, to a full-scale change in farming practices and technologies through an integrated approach to all practices that help optimize C capture, storage, and emission reduction. Farmers have many agricultural management practices to choose to develop their farming plan, including maximum groundcover, grazing management, no-till cropping, pasture and cover cropping, organic mulching, use of green manuring, residue management, biochar, agroforestry, silvopasture, use of organic manures and precise use of fertilizers, pesticides and other agrochemicals, less use of heavy mechanization livestock and manure management (Kiely 2020).

With C farming farmers use the power of the soil to sequestrate C emissions from industry, infrastructure, and households nearby. This yields a better climate, more fertile and resistant farmland, and creates opportunities for several partners in and outside the agri-food chain (The climate reality project 2019).

C farms are a wide range of farming practices across a variety of types of farms which lead to increased soil storage (Fig. 8.1). In organic farming, regenerative agriculture, permaculture, and other food production approaches, many of these practices is general. They remove C dioxide from the atmosphere and store it as plants photosynthesize. This C is either released back into the atmosphere as they die or it is retained in the soil for longer duration. The release of C is the product of many traditional farming activities, while practices known as C farming seek to do the reverse (CCI 2020).

8.3 Current Farming Systems and Their Impact on Environment

Agriculture is the major source of livelihood in Indian conditions. However, modern intensive agriculture practices and techniques are highly impacting the environment (Fig. 8.2). As we are all aware, modern intensive agriculture has increased our food affordability, increased the availability of food, assured food quality, improved biodiversity, and created more bioenergy. But leads to adds to environmental issues at the same time. Since, it is based on a high input--high output technique using high-yielding hybrid crops and sufficient irrigation water, fertilizers, and pesticides (Johnsen 2003). Worldwide, the climate is changing day by day and now it has

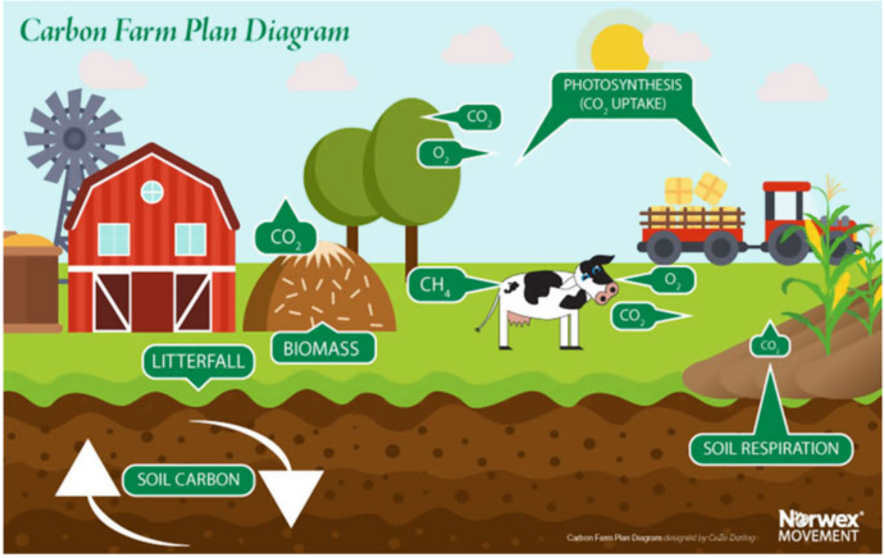

Fig. 8.1 Diagrammatic representation of carbon farm (Source: www.NorwexMovement.com)

become a challenge to living forms due to the very worst fact that every nation is trying to develop without taking into consideration its impact on the environmental and degradation and pollution of agricultural lands (Rohila et al. 2017; Bommarco et al. 2013; FAO 2002).

8.3.1 Land Degradation

The top of the farmland, which is very good and fertile, is removed due to excessive water supply. This leads to a lack of nutrient-rich soil, which has hindered agricultural production. It also affects global warming, when the silt of water bodies stimulates the release of soil C from the organic matter and particulate organic matter (Anwar 2020; Kaur and Singh 2019; Mirzabaev et al. 2019).

8.3.2 Eutrophication

It refers to the contribution to the freshwater ecosystem of organic or non-artificial substances, such as nitrates and phosphates, by means of fertilizers or sewage. It leads to the enhancement of the water body through the development of “bloom” phytoplankton. Excessive use of nitrogen and phosphorus fertilizers contributes to the overnourishment of lakes/water bodies and to eutrophication. (Kremser and Schnug 2002).

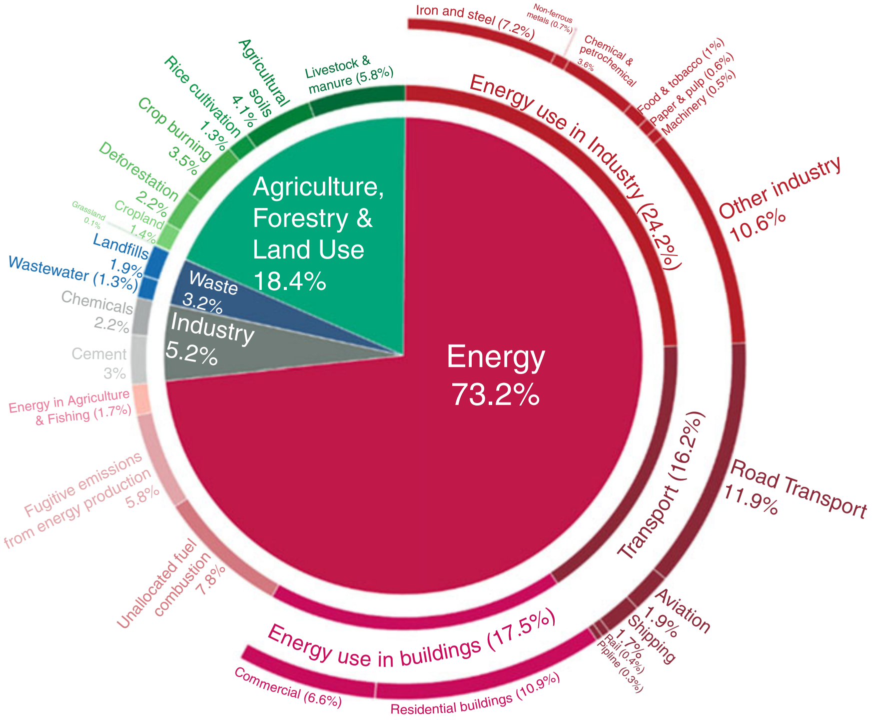

Fig. 8.2 Global GHG emission by different sectors (Source: Climate Watch the World Resources Institute 2020)

8.3.3 Excessive Use of Chemical Fertilizer

In the event of improper or inappropriate usage, fertilizers that are used for healthy and vigorous plant growth, more qualified products and many soil characteristics, such as the physical, chemical, and biological composition, cause environmental contamination. The application of large levels of nitrogenous fertilizers results in soil wash, contaminates soil water, groundwater used for drinking, creek and sea, but raises the amount of nitrogen. It also influences the species in the water and breaks the overall equilibrium of the ecosystem as that kind of water is used elsewhere. In addition, NO_2 and NO_3 and other carcinogenic compounds, such as nitrosamine accumulate in the leafy vegetables like spinach and lettuce that are produced with added soil in large volumes of nitrogen content (Onder et al. 2011).

8.3.4 Intensive and Excessive Soil Tillage

Inappropriate, heavy, and excessive surface tillage with respect to the position of the soil, soil structure, and climatic conditions without any consideration, allows the soil to shift with weather, in other hand, to cause erosion. This condition not only creates unhealthy and unfertile soils, but also pollutes lakes and fills ponds with severe environmental issues, etc. The conventional cultivation practices have led to a marked decrease in soil carbon storage, so that maintenance of agricultural activities is generally suggested as a way of increasing soil C storage, thereby alleviating climate change (Luo et al. 2010).

8.3.5 Excessive Use of Pesticide

The excessive use of pesticides for harmful insects, pests, and pathogens that are combined with soil, water, air, and food create issues with farm foods and impact both human health and the sustainable ecological cycles such that they eventually become an environmental issue (Wohlfahrt et al. 2010; Smiley et al. 2011). The degradation and boosting of crop production were caused by many pesticides. Earlier, the killing of pests included arsenic, sulphur, lead, and mercury. For example, pesticides containing Dichloro Diphenyl Trichloroethane (DDT), but also attacked the beneficial pesticides. More specifically, certain chemicals are nonbiodegradable, they are often associated with the food chains that harm humans.

Since the advent of industrialization, the relative importance of agriculture has steadily diminished, and in 2006 the services sector has, for the first time in history, taking over agriculture as the most popular economic sector in the country. Yet, we forget that if we need food to survive, we need agriculture.

Present agricultural techniques use a broad variety of additives, such as fertilizers, pesticides, fungicides, weedicides, and seed preservatives, to produce and sustain high-quality food in significant quantities. But all these compounds are hazardous and unforeseen to nontarget species, such as their toxicity, causes an ecological imbalance (Sinha et al. 2009). False agrarian activities produce emissions in essential aspects to the ecosystem as mentioned above. This means, in the event that people are susceptible, agriculture, especially modern technology, will pollute the atmosphere. As a result, mankind devised a new strategy to mitigate the harmful impacts of agriculture.

8.4 Contribution of Agricultural Sector in Climate Change

The agriculture and allied sectors represent a potentially large contribution to the total GHGemission, representing approximately 24% of the total anthropogenic emissions (Fig. 8.3) (IPCC, to be released AR5), and an increasing worldwide human population means that agricultural productivity will continue to be high when the hunger needs are fulfilled (Lenka et al. 2015).

The energy sources use in all sectors of agriculture and agricultural land management are two major anthropogenic sources of GHG emissions from agriculture. In the agricultural sector, the world livestock population and rice fields contribute significantly to methane emissions, apart from CO_2 emissions from grain and animal

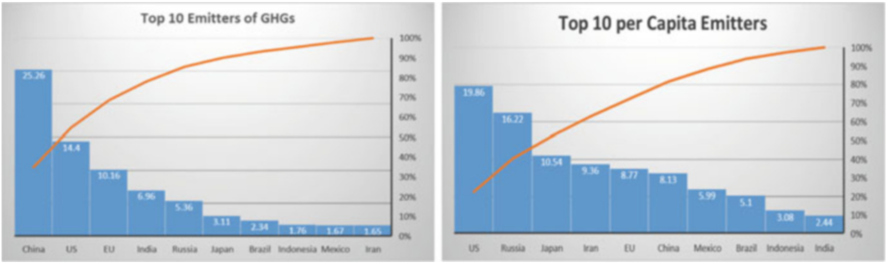

Fig. 8.3 Country wise GHG emission (Source: World Resources Institute)

waste combustion. Effective mitigation and adaptation strategies must be established in order to assess and store GHGs by sources and disposal in agriculture. Clearly, the agricultural sector is rising in scale, but the exact effect on emissions of GHGs and the potential for mitigation remains unclear. There is growing awareness among the scientific community that agriculture in general and animal processing, in particular, make a major contribution to the emission of GHGs (Fig. 8.4) (Bell et al. 2014; Bellarby et al. 2013; Galloway et al. 2007).

8.4.1 Methane Emission from Rice Field

All over the world, developing countries are thebiggest rice producers and they account for around 94% of methane emissions. Scientists have tried various rising conditions to model and analyze GHG emissions from rice fields (FAOSTAT 2013). In estimating rice fields GHG, however, due to various soil and climate situations and crop management methods, there are uncertainties. So, selection of minimum CH_4 emitters cultivars, tillage reduction uses of organic manures along with inorganic fertilizers and SRI (System of Rice Intensification) method of rice cultivation are the possible ways to reduce CH_4 emission.

8.4.2 Livestock Production and Methane Emission

Livestock sector contributes Globally, 18% (7.1 billion tonnes CO_2 equivalent) of GHG emissions. Just 9% of three contributions from the agricultural sector to climate change are 42 global CO_2; it produces 65% oxide (N_2O) and 35% methane (CH_4) with a global warming potential of 310 and 23 times CO_2 global (GWP), respectively (Sejian et al. 2011).

CH_4 is released as a by-product of the natural digestion phase of animals in which the food eaten by the animal is fermented by bacteria residing in the digestive system. CH_4 is a by-product of enteric fermentation. Improved management practices and improvements in livestock demand for dairy products and meat would also influence future CH_4 pollution (Sejian et al. 2011). The total livestock

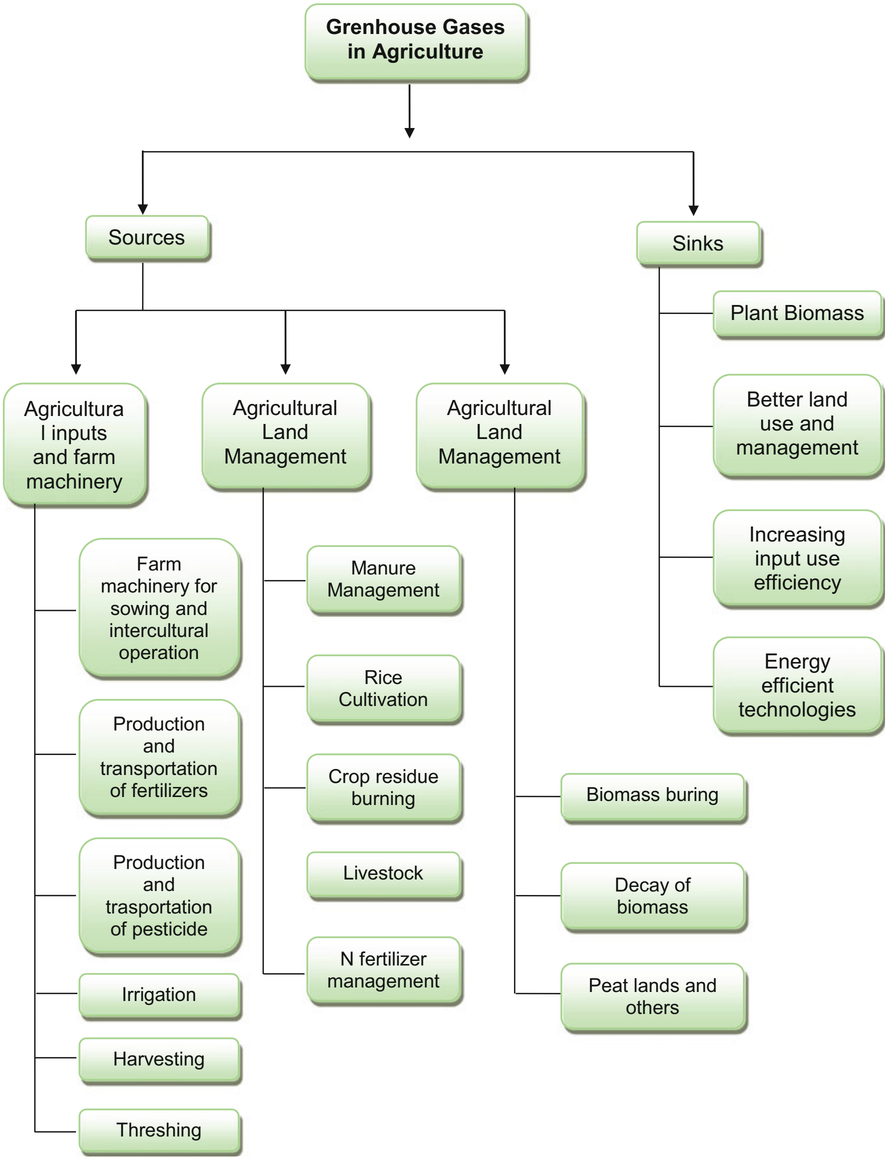

Fig. 8.4 Diagrammatic representation of different sources and sinks of GHGs in Agriculture, Forestry, and Other Land Use (AFOLU)

population generates the majority of enteric CH_4 among species (Johnson and Johnson 1995).

N_2O emissions from animal production have three possible sources (Swamy and Bhattacharya 2011). They are (a) cow itself, (b) agricultural manure stored and refined, and (c) free-range grass-free dung and urine. The ability of the manure to produce methane varies by the animal type, and feed quality, e.g., swine slurry produces more GHG than bovine slurry. (Dinuccio et al. 2008).

Overall, the use of synthetic fertilizer in agriculture rise by more than nine from 0.07 to 0.68 Gt CO_2/year from 1951 to 2010 compared with agricultural produce, and pollution of synthetic fertilizer rises too (Tubiello et al. 2013a, b). Taking into account the existing trends, after enteric fermentation, synthetic fertilizers can become a major source of contamination relative to the manure deposited on grassland in less than 10 years and the second-largest in any category of agricultural pollution. Agriculture and allied sectors contribute 4–6 tg N/year to N_2O emissions globally, from both primary and secondary sources of GHG emissions (Sharma et al. 2011).

8.5 Present Scenario of C Trading in Indian Agriculture

C trading is a market-based GHG mitigation process that contributes to global warming, in particular C dioxide. The credit could then be sold in the form of countries and companies which obtain C credits by pollution reduction. The C market of India is one of the world's fastest-growing and has generated about 30 million C credits, the second-largest transacted amount throughout the world. The Indian C trade industry is rising faster than even IT, biotechnology and BPO industries. Around 850 Rs 650,000 million investment programs are ongoing. C is now traded on the multi-commodity market in India as well. (Khadka 2019; Nugent 2019).

India has earned hundreds of millions of C credits or pollution control certificates (CERs) by investing in low-C technology, converting to renewable energy, and protecting forests. However, as was the case under the previous climate agreement-the Kyoto Protocol-the Madrid Conference was to finalize the criteria for the future global C economy as part of the Paris Agreement. Under the Paris Agreement, India has promised to reduce the emission intensity of GDP by 30--35% by 2030 and to create an additional C-sink of 2.5–3 billion tonnes of C-dioxide equivalent by 2030 by additional forest cover (Aggarwal 2019).

The COVID-19 pandemic lockdown in India is expected to decrease by about 8% C emissions in this year (The Hindu 2020). The pandemic has raised numerous problems but has helped the economy to start-up, restore communities by reconstruction plans and concentrate on climate change and the environment.

8.5.1 C Trading Status of India

India is the primary beneficiary of C trading and it is estimated that after some time India will receive between $5 billion and $10 billion from C trading. It is about time that India formed an acceptable strategy to deal with C trading. India accomplished a

21% reduction in the C-emission rate of its GDP between 2005 and 2014, thereby meeting its voluntary pre-2020 goal.

Indian factories were able to cash in on the unexpected C-demand surge, making it a favorite spot for C-credit buyers. India is expected to benefit from C exchange (22,500 crores to 45,000 crores) for at least $5 trillion to $10 trillion over a period of time. India is also the major beneficiaries of whole world C trading through the Clean Development Mechanism (CDM), accounting for around 31%of total world C trade. (https://www.civilsdaily.com/story/climate-change-building-for-paris-conference/).

8.5.2 C Market Potential for India

In June 2008, the Government of India initiated its National Action Plan on Climate Change (NAPCC) with eight missions aimed at ensuring energy stability, economic development, biodiversity conservation, and climate resilience. These missions are:

1. National Solar Mission
2. National Mission for Enhanced Energy Efficiency
3. National Mission on Sustainable Habitat
4. National Water Mission
5. National Mission for Sustaining the Himalayan Ecosystem
6. National Mission for a "Green India"
7. National Mission for Sustainable Agriculture and
8. National Mission on Strategic Knowledge for Climate Change.

The planning commission formed a steering committee to develop a low C inclusive growth policy for India's twelfth five-year plan. In its interim report, the low c inclusive development strategy expert group predicts national pollution mitigation potential for various sectors by 2020 under two scenarios, namely 8% and 9% of annual GDP expansion, respectively. Energy, transport, iron and steel, cement, oil and gas, household, waste management, other production, and household are all sectors included. In the following areas, the expert committee did not include or consider very limited potential: energy supply, chemical manufacturing, fugitive emissions from halocarbon and sulphur hexafluoride refining and usage, building, solvent use, mining/mineral production, and emissions from fuels (Ministry of Environment, Forests and Climate Change 2014).

8.6 Climate-Smart C Farming Techniques for Environmental Security

A report on global warming was issued by the Intergovernmental Panel on Climate Change (IPCC) in 2018, outlining the need for behavioral and technical change to restrict the world temperature increase to 2 ° C by the turn of the century, a goal that is most likely not to be reached. Global GHG emissions are forecast to exceed 52--58

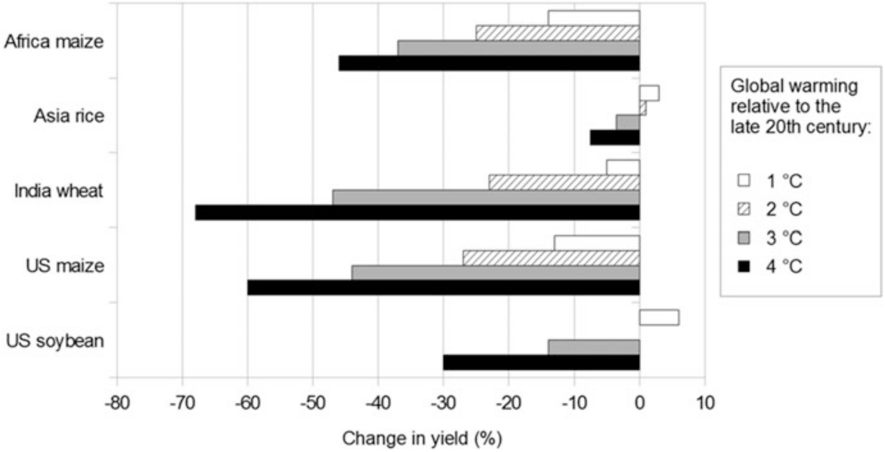

Fig. 8.5 Change in yield of different crops due to global warming. (Source: p. 161, in: Sec 5.1 Food Production, Prices, and Hunger, in: Ch 5: Impacts in the Next Few Decades and Coming Centuries, in: US NRC 2011)

Gt CO2 eq by the year 2030. Regenerative agriculture is a way to achieve this further. It uses soil strength to sequester ambient C into underground storage, also known as “C smart” farming. It can be a ray of optimism in the society’s battle against the forthcoming changing climate crisis, with enough research to resolve existing disparities in knowledge (IPCC 2018a, b).

Agriculture and allied sectors have one of the largest C footprints from all sectors; it accounts for 23% of global emissions, along with forestry and other forms of land use. Via pesticide use, agricultural production emits GHGs,such as nitrous oxide. However, agriculture could have the ability to alleviate the climate crisis with the right management strategies while reaping other forms of benefits. Conservation agriculture, or C farming, is a specific activity. by following the conservation agriculture get benefits to c conservation in soil, reversing the effect of changing climate requires Soil Organic Matter (SOM) rebuilding and preserving depleted biodiversity of soil on a sustainable basis, which results in both C drawdown and improved water cycle (Fig. 8.5) (Sim 2020; EPA 2020).

It aims to enrich soil quality by introducing practices of land management that foster Soil Organic Matter(SOM) proliferation. This not only prevents soil erosion but also encourages C sequestration capability deep into the soil, which leads directly to mitigation of climate change. The minimum tillage of soil is one method of conservation agriculture practices. The process of turning over and breaking up soil up to 10 in. deep-is soil tilling. Used sparingly, hardened soil may be loosened and nutrients properly introduced into it, increasing crop yield. Yet, its use contributes to soil depletion in the long term, displacing plant organic matter, micro and macroflora and fauna within the soil system. The effect is unhealthful, bare, and uncovered soil that is quickly eroded by wind and water (Foresight 2019). History has demonstrated how damaging bad soil management practices can be, soil quality and ultimately to the economy. The United States dust bowl, which formed in the 1930s, a time of extreme dust storms caused by drought, resulted from the over-ploughing of agricultural land by amateur farmers, making the land nonarable. Wind erosion has steadily created massive dust storms that have resulted in the devastation of agricultural livelihoods and the expulsion of 2.5 million people from the prairie-free areas and their large roots that have captured the earth. The dust bowl has increased agricultural instability, along with global difficulties triggered by global depression. (FAO 2020a, b).

Intact protection of soils increases water retention and circulation in soil, drought control, and water pollution control by reducing the flow of fertilizers and other contaminants to local waterbodies. Farmers without fertilizer can often create healthier soils by leaving their own devices with microbes of the soil, enable nutrient cycling and healthy crop production. The long-term introduction, as research has shown, of reduced laying can also produce more profitable crops (Spears 2018; Sim 2020).

The response to the climate change crisis could be part of tillage reduction. Soil is a natural C reservoir that can hold up to three times the C quantity of the atmosphere. Tillage disruption contributes to organic C content ascending above level, which results in C reacting to C dioxide with ambient oxygen. About 130 billion tons of carbon, or about a fourth of the C of human emissions from the ground since the industrial revolution, is estimated to have been lost worldwide. This helps C to remain in the soil by minimizing the tillage. Other activities under C farming include growing crops with the goal of enhancing soil health and quality instead of increasing crop productivity (Sim 2020).

C smart agriculture is simply a smarter way of handling land as part of the climatic solution. The depletion of 50–70% of C content initially contained in soils contributed to half of the world's liveable soil conversion for agrarian purposes. A shift in agriculture and the treatment of soil by proxy could therefore facilitate soil sequestration C and reverse the function of soil from C source to C sink (Downing et al. 2017).

As a C drain, the soil has considerable capacity. If technology is capable of moving ambient C underground, the target of reducing warming to 1.5 °C may be within reach. In comparison, C stored underground could be longer lasting than C stored in overground biomass like a vegetative cover, because the former is more likely to withstand the consequences of fire and wind like natural forces (Hoffmann 2013).

However, considering its potential like natural climate change remedy, C smart farming is not the magic that controls the effect of climate change and global warming. More decision-makers and organizations are particularly interested in using organic soil C as a natural environment approach, partly because C smart agriculture gave a number of benefits, is relatively easy to adopt and can make a major contribution to climate solutions for agriculture. However, more study is required until scientists have full confidence in C smart agriculture's capacity to tackle climate change.

8.7 Mitigation of Climate Change through C Farming

Climate change (CC) is one of the most significant phenomena today due to its serious impacts on agriculture, soil, climate and the atmosphere. Different anthropogenic activities responsible for the release of GHGs are attributed to this, which induces the greenhouse effect and contributes to climate change. It is a change in the statistical distribution of weather conditions that ideally lasts decades or millions of years (http://www.ipcc.ch/ipccrep-orts/tar/wg2/index.php?idp=689). It is detrimental to the natural habitats that provide us with oxygen, water for drinking and other uses, food and raw materials for industry (McNutt 2013).The latest dangerous effects of climate change cause disruption to more than 1700 animal species and cause ecological zone changes of an average of 6.1 km Decade^{-1} and spring advances of 2.3 days earlier Decade^{-1} (Parmesan and Yohe 2003).

The adverse effects of changing climate have not ended here, but the likelihood of severe weather events, such as drought, hurricanes, floods, and deforestation due to forest fires and droughts posed by extreme weather events will increase (Lindner et al. 2010). Scavia et al. (2002) analysed the impacts of CC on the ecosystem of marine and coastal environments and addressed their impacts on estuaries, coastal wetlands, coral reefs, and habitats in the vicinity. They said that sea-level increases, rainfall changes, ocean temperature rise, changes in circulation patterns, storm frequency and severity, and altered concentrations of C impact the marine environment by dissolving coral reefs, causing glacier melting, loss of biodiversity, and migration. Agricultural crops are also estimated to face a decline in yield, which will worsen the food security issue. The results show that Asia will experience food shortages by 2030 on the basis of general models (Lobell et al. 2008).

CC can impact food availability and food system stability, short-term fluctuations in the supply of water, and weather conditions (Wheeler and Braun 2013). Temperature-induced yield losses would include the effects of CC on food crops, which will be 30–46% at the end of this century and 63–82% by the end of the next century (Schlenker and Roberts 2009). In the next 20–80 years, another study indicated a 37% loss of yield and if C concentration rises by 450–550 ppm, it will have deleterious effects on grain quality (Erda et al. 2005). Since climate change is a threat to agriculture and crops, crop yields will decrease by up to 8% by 2050, including a 17% reduction in wheat yields, a 5% reduction in maize, a 15% reduction in sorghum, and a 10% reduction in millet yields (Knox et al. 2012).

Climate change effects on other natural resources are also being followed; for example, water resources are vanished by the rise in global temperatures, and glaciers are melting at an unprecedented pace that would bring an end to freshwater reservoirs (Piao et al. 2010; Christensen and Lettenmaier 2006). It is projected that about 5 billion out of 8 billion people will face water shortages by 2025 due to increasing climate change-related temperatures, which will change the rainfall amount, decrease snowfall time, snowfall shift, and snow melting area. The global population will decline by 2050 because of deaths due to water scarcity and poor quality (Arnell 1999).

The CC effects on biodiversity were evaluated by Coristine (2016). The possible threats for animal species are the extinction of biodiversity, urbanization-induced loss of habitat. The other implications of CC are habitat loss due to its compartmentalization by infrastructure growth. Therefore, restoring sinks for C and finding new, efficient, and cost-effective ways to sequester C (Farooqi et al. 2020).

The techniques for managing CC impacts are agricultural land use, prescribed management methods, regeneration of slightly degraded lands to natural lands, using conservation tillage, field cover, fertilizer management, crop rotations, agroforestry, green manuring, organic farming, desert salinization (conversion of desert sand into fertile soil) and soil microbe management. 50–1000 kg C is sequestered in 1 ha each year by using sustainable tillage. C sequestration (CS) is a win–win solution as it preserves marginal soils, increases soil quality and CS capacity, generates biomass, and produces crops on it (Lal 2004a, b; Bonan 2008).

(reducing emAgroforestry, afforestation, reforestation, and REDD+ (reducing emissions from deforestation and degradation) are the strategies by which we can maintain C levels to a bearable concentration, different engineering and trade-related techniques are also used for this purpose like building equipment for rainwater harvesting, water conservation strategies like drip irrigation, water desalinization, and storing C in deep soil horizons through geological storage. Trade-related strategies include C trading in which C emitter pays to the company or organizations that reduces its concentrations in the atmosphere, urban planning, developing equipment that capture GHG emissions and using alternative fuels which emit less or no C in the atmosphere (Lal et al. 2007).

The prevention of CC or the solution of all of the above problems lies in the reduction of atmospheric C concentrations. To achieve this, there are many methods, including C storage in seas, forests, or geological sequestration. Forests need a wide growing area and plenty of time to mature and sequester carbon.

There are several other techniques that assist in C sequestration, such as agroforestry in which trees are grown in conjunction with agricultural crops, crop rotation, organic farming, nutrient management, nil or low tillage, cropping, afforestation, reforestation, rainwater harvesting and saving technologies, desalination of water, desert salinization to improve C pool, C exchange t (Farooqi et al. 2020).

8.8 C Outputs in Indian Agriculture

The present assessment evaluates GHG emissions from agriculture in India over the past 50 years. From 14.81 Tg CE/year (0.12 t CE ha^{-1} $year^{-1}$) in 1960 to 38.71 Tg CE/year (0.28 t CE ha^{-1} $year^{-1}$) by 2010, emissions have risen by 161% over 50 years. This is primarily attributed to an improvement in the inputs use: inorganic nitrogen fertilizer, transitioning from traditional animal and human energy supplies to carbon-intensive diesel and electrically dependent machines. It is also because of a decline of 16% in the less carbon-intensive coarse cereals area and a 22% increase in rice cultivation. Maximum emissions of rice (23.75 Tg CE/ha) were reported among crops, while red gram (2.98 Tg CE/ha) was the lowest. Inputs of nitrogen accounted for 92 and 83% of emissions between 1960 and 2010, respectively, while efficiency of nitrogen usage decreased, indicating loss of added nitrogen as N_2O to the atmosphere. In 1960 and 2010, methane accounted for 90 and 58% of emissions, respectively, reflecting a decreasing trend over the years. The adjustment of the use of nitrogen fertilizers and steps to minimize methane emissions alone will also significantly minimize the C footprint of the operation of production of crops. There is also sufficient space for energy sources to minimize pollution (Sah and Devakumar 2018).

Agriculture, which contributes about 20% of the national Gross Domestic Product(GDP) and provide livelihoods to almost two-thirds of the population, is one of the important contributing sectors of the Indian economy (ICAR 2015). Equally significant is agriculture's contribution to national food security. After the Green Revolution (GR), India is self-sufficient in food grain production, but sustaining this performance was challenging because of the increasing scarcity of resources, including labor, water, electricity, and rising production costs (Saharawat et al. 2010). Increased use of production inputs, such as mineral fertilizer, has made Indian agriculture more GHG intensive. Currently, 18% of India's overall GHG emissions account for agricultural output (INCCA 2010). Latest projections report that the world supply of food could rise by 70% in order to satisfy the projected demand for food for the world population of 9 billion by 2050 (CTA-CCAFS 2011). With a huge and tremendously growing population of 1.3 billion, it is clear that India's food grain production system will be key to the world-wide challenge of supplying ample healthy and nutritious food while minimizing the emission of GHGs. However, given the growing population and evolving dietary habits, the GHG emissions from different sectors of agricultural and their production in India are likely to modify.

The majority of agricultural GHG emissions in India mostly occur at the primary stage of production (Pathak et al. 2010) and are produced by the manufacture and use of agricultural inputs, agricultural machinery, land disturbances, waste management, and crop irrigation management. To increase yields and boost harvests, these methods are used. Farming may also act as an effective climate change mitigation tool because of its direct contribution to global GHG emissions (Smith et al. 2013).

The key sources of GHG emissions in Indian agriculture were found to be livestock and rice production, with a national average of 5.65 kg CO_2eq kg^{-1} rice, 45.54 kg CO_2eq kg^{-1} mutton meat and 2.4 kg CO_2eq kg^{-1} milk. India's production of cereals, fruits, and vegetables emit comparatively less GHGs with a result of <1 kg CO_2eq kg^{-1} (Vetter et al. 2017).

8.8.1 Climate-Smart Mitigation Strategies

The ultimate three cost-efficient mitigation steps with the ability to mitigate around 9% of India's GHG emissions from the agricultural and livestock sector in the year 2012 allow more productive use of nitrogen fertilizers, zero-tillage cultivation and efficient water conservation, which can save Rs. 6500, 4200 and 770 per tonne of CO_2 equivalent. Past research shows that India's nutrient-use-production is just about 30% compared to other countries total production efficiency. The key explanations for this are unequal and inadequate ways of inorganic fertilizer application coupled with overreliance on the one type of N source (Jain 2019a, b; Liu et al. 2016).

By supporting a site-specific nutrient management approach, India may increase fertilizer N [nitrogen] consumption efficiency. Zero tillage is a technique where farmers reduce the disruption of the soil by tillage (also known as no-till farming) (also known as no-till farming). It can be used in the production of barley, maize, cotton, and sugarcane. Without losing yield, managing paddy water by allowing the farm to dry after irrigation instead of holding continuously flooding rice fields will minimize CH_4 emissions. This emission reduction method also does not require more electricity for pumping water where groundwater is used for irrigating rice fields.

8.8.2 Challenges in Adoption

The adoption of technology by farmers is heavily influenced by the political and socioeconomic environment (Fig. 8.6). By means of adequate legislation, incentive structures, and institutional setup, the government should encourage these. It is important to avoid counterproductive policies. Basically, effective use of fertilizers comes from the correct form of fertilizers, such as slow-release N fertilizers, which are costly. Zero-tillage would also take time to demonstrate advantages and farmers

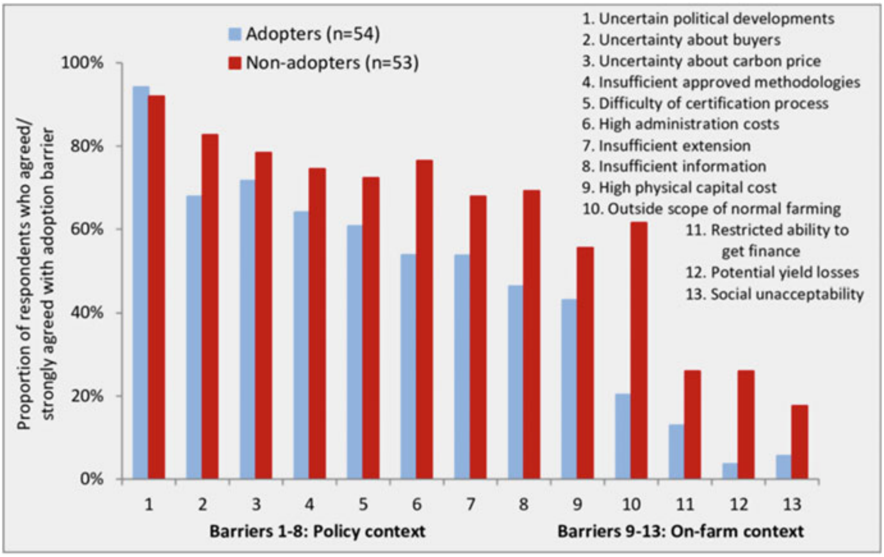

Fig. 8.6 Barriers for adoption of C farming practices (https://www.researchgate.net/publication/270573098_What_are_the_barriers_to_adopting_carbon_farming_practices)

would need to be patient. Since the least concerned farmers are about environmental benefits, the implementation of these practices would require incentives. Consolidated initiatives are also required by the government, the private sector, nongovernmental organizations, farmers and agricultural societies, and so on.

8.9 Government Policies to Minimize the C Emissions

8.9.1 Kyoto Protocol

The Kyoto Protocol was committed by the UK, an international convention that takes climate change into account. The Protocol commits countries to an immediate solution to minimizing their emissions of GHGs (UNFCCC 2019).

The aim of the Kyoto Protocol was to include an option for UNFCCC (United Nations Framework Convention on Climate Change) countries to follow methods to set goals for monitoring and calculating GHG emissions within the region. Most of the UN Member States agreed on the terms, but the United States did not ratify the protocol while accepting the definition, believing that their implementation would result in a reduction of their GDP. As a result, the US is not bound by the Protocol and, as such, is not responsible if it does not meet the pollution goals (UNFCCC 2019).

8.9.2 EU Emissions Trading Scheme

In order to tackle climate change, the EU C trading system is part of the strategy. It makes it easier to reduce GHG emissions in a cost-effective manner. A fixed limit on the amount of clear GHGs that can be produced is given by the scheme. Organizations can buy pollution allowances within the cap and, depending on the market, these allowances can be exchanged between businesses (EU-ETS 2015; Carson 2018).

8.9.3 Climate Change Act 2008

To legally guarantee the elimination ofGHG emissions, the Climate Change Act 2008 was adopted. A summary of the Climate Change Act allows the government to adopt methods to limit both C dioxide and GHG emissions. In addition, the act holds that it is the duty of the government to plan for climate change. This is applied by risk analyses of the UK climate change that can be updated every 5 years. GHG emissions by 2050 could be decreased by 80% from 1990 levels. C budgets are a constitutionally binding way of reducing over a five-year cycle the cumulative volume of GHGs that the United Kingdom will produce. The Act stands in tandem with the Climate Change Commission (Carson 2018).

8.9.4 The C Plan

The C Plan was developed by the Government in December 2011 with plans to achieve reductions and to fulfill the 2050 target. This strategy is consistent with the 2008 Climate Change Act which points out how the C reduction goals will be accomplished (Carson 2018).

8.10 C Stabilization

C stabilization is the collective term for C sequestration and storage maintenance mechanisms or processes in an area. C stabilization ensures that the possible degradation of organic C by microbial respiration, erosion, or leaching is minimized (Dignac et al. 2017). Different pathways and processes for the stabilization of soil C have been postulated by numerous workers. Others are best understood, while others need knowledge for verification and confirmation at the experimental level. Moreover, it was not possible to compare the relative value of each of the proposed processes in the soil and atmosphere in question. There has been great improvement in identifying the physical processes of soil C stabilization, in particular those concerning soil aggregate formation and its interactions between SOM and soil minerals. The role of plant rhizosphere and roots, soil biodiversity like micro and macro flora and fauna and the contribution of brown and black C, recalcitrant, inorganic and refractory C, and humic substances(HS) compounds, in particular hydrophobic HS compounds, to soil C stabilization is less known (Goh 2004).

8.10.1 Mechanisms of C Stabilization

The latest suggested soil C stabilization mechanisms are divided into mechanisms of physical, chemical, and chemical/biochemical defense or their combinations.

Physical Stabilization These processes are primarily attributed to soil organic C (SOC) interactions with a soil mineral matrix that creates tight chemical connections or makes soil C unavailable to decomposing organisms or their enzymes. These processes preserve and safeguard up to half of the sum of SOM in soils (Elliott et al. 1996). Two main classes of pathways accountable for the preservation of organic compounds and soil C from clay minerals were allocated by (Stevenson 1994). Both are physicochemical stabilization by sorption of organic matter into clay surfaces creating organic mineral complexes and physical stabilization by penetrating organic matter into interlayer spaces of expanding clay minerals, thereby encapsulating and protecting organic matter, thus inhibiting the ability to de-layer.

Chemical Stabilization SOM can be stabilized by contact with salts, by its natural recalcitrance and by occlusion in aggregates against decomposition. These pathways are due to the processing by fires of charcoal (or black C) and of biologically inert or recalcitrant and refractory compounds and very slowly decomposable HS and organic compounds, such as lipids (e.g., waxes, cuttings, sub-liners) and plant-based chitin, soil fauna, and soil microorganisms.

Biological Stabilization The processes by which SOC can be biologically stabilized depend on the decomposition of the mineral process of the soil and the chemical structure of the soil-added organic residues. There is more to the stabilization of decomposed organic matter than that of new organic matter. The complexes formed by some linkages between organic and mineral matter are organo-mineral complexes. H bonding, ligand exchange, and bridges of polyvalent, cations can be the different bonding mechanisms found in organo-mineral complexes (Karsten et al. 2007).

As the mechanism helps to sequester and retain C in the soil and thereby avoids C mineralization, C stabilization can tackle climate change. While the processes behind C stabilization still remain elusive, physical stabilization protects more than half of the total soil carbon. In C fixation, organo-mineral complexes play a significant role. Prevailing strategies for long-term C preservation are physical stabilization and defence mechanisms, such as occlusion to the surface of microaggregates and absorption into organo-mineral complexes. The complex between Fe-oxides and C of the short-range order leads to the significant stabilization of C in the terrestrial ecosystem (FAO 2020a, b).

8.11 Future Prospects of Research

Key problems need to be resolved by future research efforts in the field of C farming improvement: farm management scenarios demonstrate that emission intensity can be minimized while preserving farm productivity, many farmers and land managers, and their key influencers, have become more aware of farm emission management, research into emerging technologies and emission reduction practices for farmers.

Research has shown that inhibiting methane production in ruminants can increase the growth and efficiency of an animal and lower application rates of manure have been found to minimize pollution while preserving farm productivity. Replacement rates or fertilizer equal value of varied organic materials with potential for use as soil fertility restorer inputs. C agriculture can take many forms. The simplest practices require changes to the development of annual crops. While all of these adaptations have comparatively low sequestration capacity, they are commonly available and readily implemented, and thus, if practiced on a global scale, have excellent potential for reducing climate change.

Similarly, grazing systems, such as silvopasture is easily replicable, do not entail major improvements to the human diet, and key techniques in the C farming arsenal can be important considering the amount of agricultural land devoted to pasture worldwide. But agroforestry activities and seasonal crops, by far, offer the greatest sequestration prospects.

8.12 Conclusion

- C farming requires activities that are considered to increase the pace at which CO_2 is extracted from the environment and converted to organic matter from plants and soil. When C gains resulting from improved land management or conservation activities outweigh C losses, C farming is successful.
- The consequences of climate change can be felt on a day-to-day basis, especially by farmers, but very few ways to resolve this challenge have been discussed. One approach to reducing the volume of GHGs that are stored in the atmosphere is agriculture. Agriculture's own footprint has been minimized by reducing tillage, expanding field rotations, and planting cover crops. This C collected is then transformed into an organic matter of plant material and/or soil.
- Many of these C agricultural methods have now been applied internationally on a scale of millions of hectares. These are not small or marginal initiatives, but win--win strategies that include food and feed, while promoting community self-reliance, generating employment, protecting habitats, and preserving polluted land while sequestering carbon, lowering pollution, and eventually leading to an environment that will remain vulnerable to human civilization. Perhaps as essential for a sustainable future, these crops and practices will lead to wider social agendas, such as equality of women, food sovereignty, and climate justice.
- C farming is a long-term and short-term agricultural method for the sequestration of C and the continuous enhancement of soil quality. The growing proof points to the validity of C farming as a practice of storing carbon. An international network of hubs installing working examples of C farming needs to be established. It is possible to expose the fundamental mechanisms of C storage as inspired by C farming.
- C farming, however, remains a significant technology that improves soil conditions, regulates soil degradation, and reduces the cost of production associated with tillage, even though C stabilization and storage is questionable in some areas and some farming systems, and these are sufficient reasons to encourage step-by-step conversion by implementing C-enhancing resource conservation technologies. While the real potential of C farming as a C offset technology needs a more thorough understanding of practical relationships, it is better to implement agricultural practices that sustain and restore soil functionality than practices that kill it. The key objectives of a sustainable C farming system should be global food protection, global environmental sustainability and a farmer-level increase in livelihoods.

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9

Judicious Soil Management for Having Improved Physical Properties of Soil and Input Use Efficiency

R. S. Chaudhary, Jitendra Kumar, Alka Rani, and Seema Bhardwaj

Abstract

Soil physical constraints and ever declining soil physical environment is seen as one of the major threats to the world food security. At the global level, about 6.17 billion hectares of land is affected by soil physical constraints and degradation by soil erosion, and India is no exception to it. Approximately, 90 million hectares (Mha) of the area in India too is suffering from various soil physical constraints like shallow depth, subsurface hardpan, temporary waterlogging, surface crusting, etc. These soil physical constraints need to be appropriately managed by the adoption of suitable problem-based techniques like mulching, suitable tillage, compaction, addition of organic manures, etc. so that their productivity could be improved. Apart from that, the shrinking availability of input resources like water and nutrients for agriculture are compelling the need of improving their use efficiency in agriculture. Several technologies are in practice either individually or in an integrated way to augment the efficiency of these inputs. The primary objective of this chapter is to bring all possible tools and techniques available to manage the soil, nutrients, and water while maintaining the physical soil health intact. Toward this, several methods are available with proven effectiveness in improving the input use efficiency. For improving water use efficiency (WUE), e.g., mulching decreases the loss of soil moisture and saves the surface soil against the direct beating impact of raindrops, thus, avoid the surface sealing which increases the water infiltration and its prolonged storage in the soil profile. The higher irrigation efficiency of approximately 80–90% can be attained by farmers by using micro-irrigation system. The drip irrigation system results in reductions of water use by 30–60% and an increase in crop yield by 20 to 50% in

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various crops. Sensors-based application of water can effectively save irrigation water and improve WUE. On the other hand, low efficiency of fertilizers/ nutrients is found to push up cultivation cost and pull down the profits in agriculture. As far as Nutrient Use Efficiency (NUE) is concerned, the integration of various nutrient sources through Integrated Nutrient Management (INM) is found to enhance the productivity of crops and use efficiency of the nutrient resource through the integrated application of fertilizers, bulky manures (organic or green), legumes, and crop residues. The slow-release fertilizers, release the desired nutrient/s in a regulated, delayed pattern to match with the sequential needs of plants for nutrients. The objective should be to apply the inputs at right rate, right time, and right place. This way, they enhance the use efficiency of nutrients and increase crop yields. The ultimate aim is to augment the use efficiency of resources like water and nutrients without wastage of either and simultaneously keeping soil health intact.

Keywords

Soil physical health · Water use efficiency · Nutrient use efficiency · Mulching · Conservation agriculture

Abbreviations

AEN	Agronomic efficiency of nitrogen
AgNUE	Agronomic nutrient use efficiency
AICRP	All India Co-ordinated Research Project
Al	Aluminum
AWC	Available water capacity
B	Boron
BD	Bulk density
Ca	Calcium
CA	Conservation agriculture
CMI	Carbon management index
CPI	Carbon pool index
CRF	Controlled release fertilizer
CT	Conventional tillage
Cu	Copper
CWP	Crop water productivity
FDR	Frequency domain reflectometer
Fe	Iron
FIRB	Furrow irrigated raised bed
FUE	Fertilizer use efficiency
FYM	Farm yard manure
HI	Harvest index
INM	Integrated nutrient management

IoT	Internet of things
K	Potassium
LI	Liability index
LSD	Least significant difference
LTEs	Long-term experiments
Mha	Million hectares
Mn	Manganese
Mt	Million tonnes
N	Nitrogen
NE	Nutrient expert
NPs	Nanoparticles
NUE	Nutrient use efficiency
P	Phosphorus
PFPN	Partial factor productivity of nitrogen
S	Sulfur
SOC	Soil organic carbon
SOM	Soil organic matter
SRF	Slow-release fertilizer
TDR	Time domain reflectometer
UpE	Uptake efficiency
UtE	Utilization efficiency
WSA	Water stable aggregates
WUE	Water use efficiency
Zn	Zinc
ZT	Zero-Tillage

9.1 Introduction

The soil-related constraints, such as land degradation due to erosion, chemical degradation, and physical constraints, are adversely affecting the sustainable crop production in the world. At the global level, the soil physical constraints like shallowness (1.91 billion ha), vertic properties (0.32 billion ha), erosion (2.19 billion ha), and hydromorphy (1.74 billion ha) remains major factors of lowering soil productivity. In India, the physical constraints of soil, such as shallow depth, subsurface hardpan, temporary water logging, surface crusting, etc. are affecting about 90 m ha area. Besides this, ever-mounting human population and existing climate change scenarios are complicating further the challenges for sustainable production of food, fiber, fodder, and timber to meet the proportionately rising demand of the global natural resources that are already undergoing rapid degradation. The major question before us pending to be answered in the forthcoming few years is whether agriculture could be able to supply the world population with the required quantity of food, with the additional demand exceeding four billion tonnes annually.

Achieving more yield from a unit area with more crop per drop and more yield per unit nutrient input remains the top challenge before researchers, agriculturists, and peasants across the globe. In this domain, the lower efficiency of the chemical fertilizers and poor response of some soils/fields to fertilizers are the big constraints and bottlenecks responsible for low production and indicates soil health deterioration. It can be highly improved by fertilizer management as well as by soil and irrigation management. Since the nutrient's uptake efficiency is water-dependent, it influences water demand. Plant water requirement, to a larger extent, is governed by nutrient supply and size of crop canopy. An appropriate quantity of nutrients applied, develops higher osmotic pressure inside the plant cells that enhances the drought resistance. Nitrogen (N), being an integral part of plant DNA, chlorophyll, and proteins, plays a key role in cell metabolism, photosynthetic capacity, and yield. Potassium (K) plays a crucial role in proper functioning of stomata presents in the leaves which further regulates water loss, and therefore, an optimal supply of K is essential for conserving water. Phosphate (P) nutrient stimulates the early growth of plant roots, which is essential for extracting water from the deeper soil layers.

Therefore, improving the use efficiency of nutrients and water using different tools and techniques can offer better alternatives to provide crops with an adequate quantity of water, the majority of nutrients (macro and micro) that can further reduce the irrigation amount and dose of chemical fertilizers. It may simultaneously create favorable soil physicochemical conditions, a healthy soil environment, and maintain the soil and nutrient balance for longer periods, thus sustaining the desired crop productivity. Conservation agriculture, with residues, retained on the surface after harvesting the crop, not only enriches soil organic carbon but also improves soil quality along with protecting physical degradation. The adoption of the available and advanced tools and techniques for enhancing the use efficiency of natural resources could produce a greater yield while saving the inputs is the need of the hour.

The primary objective of this chapter is to bring all possible tools and techniques available to manage the soil, nutrients, and water while maintaining the physical soil health intact. Therefore, the techniques and practices, to improve the physical health of the soil and use efficiency of vital inputs like water and nutrients have been discussed in this chapter.

9.2 Scope of Improving Soil Physical Properties and Input Use Efficiency in India

Use efficiency of two vital inputs, viz. water and plant nutrients, is highly interrelated to the soil's physical environment. Better soil structure has enough space for retaining and exchange of water and soil air. Better aggregation and porosity are helpful in better retention and transmission of water and its prolonged availability to crop plants (Kumar et al. 2018). It is well-known that the nutrients in the soil, whether native or applied through fertilizers or manures, are taken up by plants as a

Table 9.1 Distribution of area (in lakh ha) of Indian soils under different physical constraints

Soil physical constraints	Area (lakh ha)	Main states affected
Shallow depth	264.0	Maharashtra, Andhra Pradesh, Gujarat, Kerala, West Bengal
Soil hardening	215.7	Andhra Pradesh, Bihar, Maharashtra
High permeability	137.5	Rajasthan, Gujarat, West Bengal, Punjab, Tamil Nadu
Subsurface hardpan	113.1	Maharashtra, Bihar, Punjab, West Bengal, Rajasthan, Tamil Nadu
Surface crusting	102.5	Haryana, West Bengal, Odisha, Punjab, Gujarat
Temporary waterlogging	62.4	Maharashtra, Madhya Pradesh, Kerala, Punjab, Gujarat, Odisha

Data source: Painuli and Yadav (1998)

soil water solution. They are imbibed as mass flow along with water available in the rhizosphere. Therefore, if the soil's physical environment is sound with better aggregation, optimum porosity, and lower bulk density, the movement of water, air, and plant nutrients into the rhizosphere is easy and so is their uptake by the plants. In the absence of sound soil structure, there is more likelihood of these resources lost with runoff without proper assimilation into the soil.

The degradation of soil physical health and low use efficiency of crucial inputs, *i.e.*, water and nutrients are the serious problems of Indian agriculture. Approximately, 90 million hectares (Mha) area in India is having the problem of soil physical constraints (Indoria et al. 2017). The distribution of area, of Indian soils under different physical constraints, is given in Table 9.1. Soil erosion causes the formation of shallow and gravelly soils in some areas. The predominant soil structure associated problems, such as crusting and hardening in sandy loam alluvial, red and laterite soils, slow permeability of clays (Vertisols), and high permeability of desert soils with sand and loamy sand texture, are in existence. Subsurface hardpan may develop as a result of clay illuviation to the subsoil horizon and heavy tractor load and trafficking in the field (Indoria et al. 2017). The low infiltration capacity of Vertisols may lead to temporary waterlogging during heavy rainfall. Therefore, these soils need to be properly managed to overcome their physical constraints and improve crop yield.

According to the Ministry of Water Resources, River Development, and Ganga Rejuvenation, the water use efficiency (WUE) of Indian agriculture is approximately 38% which needs to be enhanced as water availability for agriculture is becoming scarce due to population growth and its diversion for other domestic and industrial purposes. The WUE of different irrigation techniques is depicted in Fig. 9.1. Conventionally, the irrigation is done through surface irrigation methods, either as uncontrolled flooding or as controlled flooding methods like borders and furrows, check basins, etc. in most of the areas in India. These surface irrigation methods have very low irrigation/application efficiency ranging from 35 to 65% as more water is lost through evaporation and deep percolation. The micro-irrigation system like drip or sprinkler has higher irrigation efficiency up to 80–90%. The area under water uses

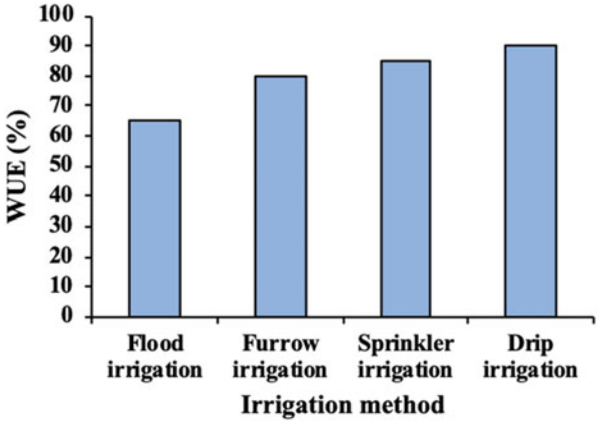

Fig. 9.1 WUE of different methods of irrigation. Data source: Central Water Commission (2014)

Table 9.2 Recent status of the NUE in agricultural ecosystems

Nutrient	NUE (%)	Cause of low efficiency
Nitrogen (N)	30–50	Immobilization, volatilization, denitrification, leaching
Phosphorus (P)	10–20	Fixation in soils
Potassium (K)	50	Fixation in clay lattices
Sulfur (S)	8–12	Immobilization, leaching
Zinc (Zn)	2–5	Fixation in soils
Iron (Fe), Boron (B), Copper (Cu), Manganese (Mn)	1–2	Fixation in soils

Data source: Meena et al. (2017)

an efficient micro-irrigation system is only 10.3 Mha which is still very small than its potentials of 712.3 lakh ha (Priyan et al. 2017; Kumar et al. 2020). So, there is ample scope in improving WUE by embracing the efficient practices in Indian agriculture which are discussed in further sections.

Nutrient Use Efficiency (NUE) is generally defined as the crop output from each unit of nutrient input applied or observed. The consumption of NPK fertilizers in India is 134 kg ha^{-1} which is far more than the global average of 107 kg ha^{-1} (Meena et al. 2017). Only a small portion of fertilizer nutrients added to the soil is utilized by the plants as most of it is usually lost from the fields through different well-defined loss mechanisms. The recent status of use efficiency of different nutrients is mostly <20% except for N and K which is also low at 30–50% level (Table 9.2). The low NUE is responsible for crop yield reduction, economic loss, and environmental pollution.

9.3 Management Options for Improving Soil Physical Properties

The soil physical environment can be made ideal by adopting site-specific management measures such as minimum disturbance to the soil, less movement of farm machines, retention of residue on or in the soil which further acts as a substrate to the soil microorganisms that makes soil well aggregate, porous, and carbon-rich. Some of them are briefly discussed below:

9.3.1 Manures and Fertilizers Management

Application of organic manures like farmyard manure, such as minimum disturbance to the soil, less movement of compost, vermicompost, etc. improves soil physical properties by increasing the soil organic matter content. Fertilizers application led to the increase in crop growth and biomass which adds organic matter to the soil indirectly. The increased organic matter content can safeguard soil from surface crusting and hardening because it improves the soil structure and stability of soil aggregates by enhanced microbial activities. The addition of phosphatic fertilizers also favors aggregation due to the creation of Al-P or Ca-P binding agents (Bandyopadhyay et al. 2009). Organic matter helps in increasing water retention in the highly permeable soils to support crop growth. Organic matter improves water intake rate and soil hydraulic conductivity in less permeable soils like Vertisols by forming stable aggregates and increasing the porosity. This may help in combating the temporary water stagnation problems during heavy rainfall in black soils (Fig. 9.2).

9.3.2 Soil Amendments

Gypsum aids in ameliorating the soil physical environment of sodic soils by exchanging the sodium-ions with calcium ions. These calcium ions help in binding

Fig. 9.2 Effect of fertilizer and manure management on soil

the soil particles together to improve the soil structure which further upgrades the soil's physical environment. This practice solves the problem of soil crusting and improves water infiltration and hydraulic conductivity of sodic soils. There are no reported physical constraints in the saline soils. However, the productivity of saline soils is increased through the leaching of salts by irrigation water and other various means.

9.3.3 Tillage

Tillage is defined as the mechanical working of soil for improving its physical environment. Tillage increases macro-porosity. Tillage helps in breaking surface crusting. Occasional deep tillage of soils helps in breaking the subsurface hardpans which can increase water conductance into deeper layers and can facilitate the growth of deeper roots. Deep ploughing is seen to be very effective when performed on very dry soil in summer after the harvest of the previous crop (Suganthi et al. 2017). However, care should be taken to practice low-intensity tillage operations so that the soil structure is not unduly destroyed.

9.3.4 Compaction

Compaction is important for increasing the bulk density of highly permeable soils. It increases micro-porosity which can aid in increasing water retention at field capacity of highly permeable sandy soils. Agrawal et al. (1991) reported that subsoil compaction of highly permeable sandy soils retarded the losses of nutrients and water and enhanced the retention of soil moisture in the rhizosphere which resulted in saving of 15–36% of irrigation water.

9.3.5 Mulching

Mulching is the practice of covering the soil surface with any material, preferably organic residues. Mulching with crop residues adds organic matter to the soil which improves soil physical environment by improving soil aggregation, decreasing soil bulk density, and moderating soil hydrothermal conditions. Mulching decreases the water evaporation from the soil. It safeguards the surface of the soil from the direct beating action of raindrops, thus, avoids the surface crust formation or surface sealing and thus increases the water infiltration. Mulching decreases soil erosion by water or wind and assists in saving the top fertile soil layer.

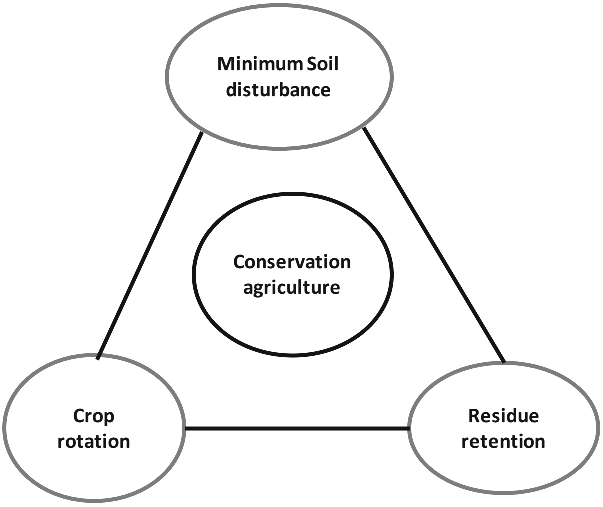

Fig. 9.3 Principles of CA

9.3.6 Conservation Agriculture

Conservation agriculture (CA) formulated on the principles (Fig. 9.3) such as minimum disturbance to the soil, residue retention, and crop rotation is very beneficial for boosting soil physical quality. It adds organic matter to the soil that enhances soil aggregation, water infiltration, porosity, and water retention capacity of the soil. Minimum soil disturbance reduces the use of tillage and passage of heavy tractor implements over the soil which avoids the formation of the hardpan in the subsoil (Meena et al. 2020). The practice of CA, thus, improves water retention, augments carbon storage in the soil, promotes nutrients recycling, reduces GHG emissions, and maintains better soil physical environments for sustainable use.

9.4 Techniques for Enhancing Water Use Efficiency (WUE)

There are numerous proven technologies to enhance the WUE of cropping systems. Even the technologies that improve soil physical properties, as discussed earlier, also improve the WUE. However, other technologies, such as the selection of crops, crop geometry, sowing time, and more effectively the efficient irrigation methods play a critical role in enhancing WUE at the field level. These techniques are briefly discussed here:

9.4.1 Crop Management

It comprises of a selection of crops as per the water availability, e.g., low water requiring crops in water scare areas, selection of more suitable cultivars, crop geometry, intercropping to harness water from deeper layers, sowing of crops to take benefit of conserved moisture, or rainfall, etc.

9.4.2 Crop Type

The crop type should be selected based on the rainfall pattern, temperature, crop duration, and irrigation water availability in a particular region. Generally, C_4 crops viz. sorghum (*Sorghum bicolor*), maize (*Zea mays*), sugarcane (*Saccharum officinarum*), and pearl millet (*Pennisetum glaucum*) have higher WUE than C_3 crops like wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), oats (*A. sativa*), pulses, and oilseeds due to the absence of worthless photorespiration process, especially under semiarid environment (Pawar and Khanna 2018). The crop water productivity (CWP) of major crops like rice (*Oryza sativa*), wheat, maize, sugarcane, and cotton (*Gossypium hirsutum*) are having the range of 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, 2020). Based on the availability of water, crop cultivation is divided into three types: rain-fed crops, limited irrigated crops, and fully irrigated crops. In rain-fed situations, crops, such as mustard (*Brassica* sp.), chickpea (*Cicer arietinum*), flaxseed (*Linum usitatissimum*), barley, and safflower (*Carthamus tinctorius*) can be cultivated in Northern India; sorghum, cotton, and safflower in Southern India and Deccan plateau, and safflower and flaxseed crops in eastern India (Singh et al. 2014). Various legume crops viz. gram, black gram (*Vigna mungo*), pigeon pea (*Cajanus cajan*), green gram (*Vigna radiata*), and beans (*Phaseolus vulgaris*) are also cultivated under rain-fed regions in India (Singh et al. 2008). The crops like wheat, rice, sugarcane, cotton, soybean (*Glycine max*), etc. are cultivated under irrigated conditions in India.

9.4.3 Variety

The varieties having higher CWP generally have characteristics like shorter duration, deep-rooted, short height, upright leaves, the low physiological requirement for water, extensive adaptability, short gap between flowering and maturity, and high photosynthetic efficiency (Dahiya et al. 2008). Few of such varieties available for Indian conditions are given in Table 9.3.

Table 9.3 List of crop varieties with higher CWP

Crop	Variety	References
Wheat	HUW 234, Lok 1, HD 2987, WH 1080	Behera et al. (2002), Shivani 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	Rathore et al. (2008)

9.4.4 Planting Geometry

Planting geometry regulates the interception of sunlight, evapotranspiration, rooting design, utilization of soil water, and other production factors like nutrients, carbon dioxide, etc. All these factors ultimately determine CWP. The planting geometry is decided based on the crop type. For example, pearl millet crop planted at the spacing of 45 × 12 cm^2 yielded higher WUE (Rathore et al. 2008). Growing the gram on raised soil beds increased the WUE by 16–17% in comparison to flat/normal beds (Pramanik et al. 2009). Several researchers reported that WUE of crops like wheat, green gram, pearl millet, and soybean can be increased by planting them on raised beds with furrow irrigation which can save 25 to 30% of irrigation water (Parihar 2004; Zhang et al. 2007). The sowing of sunflower (*Helianthus annuus*) crop having East–West direction in the Southern side of ridges had increased yield and higher CWP (Singh and Mahey 1998). Yadav et al. (2000) reported that paired row planting had a higher yield and WUE in sugarcane crop than normal plating under drip irrigation systems (Fig. 9.4).

9.4.5 Intercropping

WUE is increased by following intercropping, preferably of deep-rooted crops with shallow-rooted crops, as a relatively lesser amount of water is required toward irrigation in intercropping for equivalent yields (Singh et al. 2014). Singh et al. (2019) performed a research study on the intercropping pattern of wheat and chickpea and reported that the intercropping system gave higher WUE than sole wheat (Table 9.4). Similarly, several researchers reported increased WUE in maize + potato (*Solanum tuberosum*) intercropping (Bharati et al. 2007), pearl millet, and cowpea (*Vigna unguiculata*) intercropping (Goswami et al. 2002), wheat + maize (Yang et al. 2011), and so on.

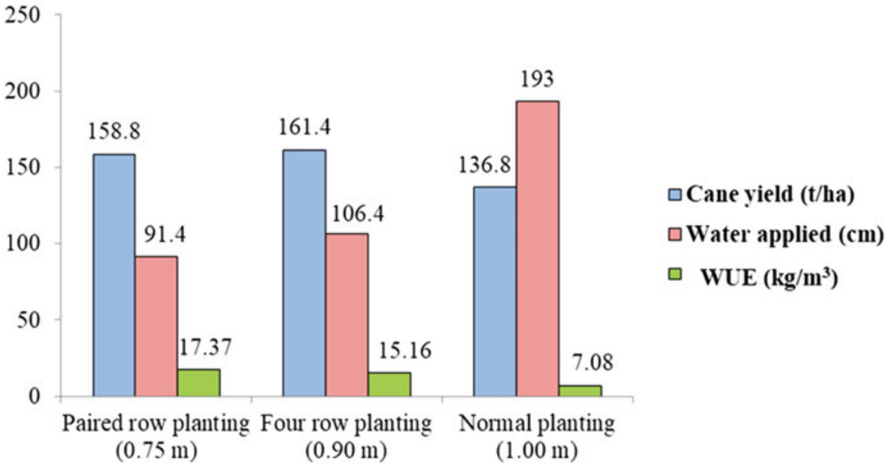

Fig. 9.4 Effect of planting design on the yield of sugarcane and WUE at Rahuri, India. Data source: Yadav et al. (2000)

Table 9.4 Effect of intercropping on grain yield and WUE of crops

Intercropping system	Grain yield of wheat (Mg ha^{-1})	Seed yield of chickpea (Mg ha^{-1})	WUE (Mg ha^{-1} cm^{-1})
Sole wheat	4.67	–	0.083
Sole chickpea	–	1.19	0.059
Wheat + chickpea (1:1)	4.35	0.66	0.109
Wheat + chickpea (1:2)	3.56	0.79	0.105
Wheat + chickpea (1:3)	2.48	0.83	0.066
Wheat + chickpea (2:1)	5.46	0.38	0.117
Wheat + chickpea (2:2)	3.82	0.59	0.098
Wheat + chickpea (2:3)	3.62	0.70	0.105
Wheat + chickpea (3:1)	5.01	0.33	0.110
Wheat + chickpea (3:2)	3.77	0.42	0.091
Wheat + chickpea (3:3)	3.96	0.54	0.102

Data source: Singh et al. (2019)

9.4.6 Sowing Time

The sowing time of the crop is an important factor that regulates crop yield and WUE. The time of sowing the crop should be adjusted such that it avoids heat and moisture stress during sensitive stages or critical growth stages viz. flowering and grain filling. The shift in the transplantation date of rice crop from first June to 21st June in Punjab can result in saving approximately 100 mm of water by combating evapotranspirational loss. In the similar manner, early maturity in the sunflower crop sown in January resulted in higher WUE than the February sown crop (Hira 2004). In rainfall regions, even the sufficient residual moisture in the soil after reaping of a crop can be made use of, by adjusting the time of subsequent crop-sowing accordingly.

9.4.7 Fertilization

The absorption of nutrients by plant roots is heavily regulated by soil moisture conditions as maximum absorption occurs at or around the field capacity. Better root growth, on account of good fertilization, can enable the plants to extract moisture from deeper soil layers. In this regard, P nutrition plays a great role in root proliferation. Chaudhary et al. (2018) recorded an increase in WUE of chickpea under variable P doses up to 40 kg P_2O_5 ha^{-1} along with moisture conservation practices in Vertisol of semiarid central India. Optimum fertilization can effectively enhance the crop yield and crop resistance to counter diseases and insect–pest that further improves the WUE. Kumar et al. (2003) documented the increase in WUE with increasing dosage of N from 0 to 150 kg ha^{-1} in pearl millet. Rani et al. (2019) found higher water productivity with an increase in N dose reaching 120 kg ha^{-1} in wheat. Both P and N improved WUE under mild moisture stress situations by increasing root growth, and grain yield (Zhang and Li 2005). K too plays a key role in imparting drought resistance and increasing WUE (Li et al. 2001). The application of S @40 kg per hectare in chickpea resulted in maximum CWP (Singh et al. 2004). Therefore, integrated nutrient management with the optimum dose of each nutrient to match the available moisture content of the soil is essential for enhancing WUE.

9.4.8 Weed Management

Weeds compete with the crop of interest for resources, such as water, light, and nutrients, thereby adversely affecting the growth of the target crop. The weed control should be done to decrease the loss of water through transpiration from weeds and to augment the obtainability of resources to the target crop that will enhance crop yield and WUE. Nadeem et al. (2007) found that weed control through manual weeding or herbicide application yielded higher WUE than uncontrolled treatment. Analogous observations were recorded by Singh and others (2004) in gram and Reddy and others (2008) in red gram. In many studies, the manual weeding and placing the uprooted weeds as mulch in the inter-row spaces have been found to trigger the WUE of the crops.

9.5 Irrigation Management

It is the procedure of deciding when and how much irrigation water should be put into the crops. Appropriate irrigation scheduling is crucial for maximizing WUE. Irrigation scheduling is crop-specific as each crop varies in water demand based on its physiological mechanisms, growth stages, genetic constitution, weather, and the type of soil (Ali and Talukder 2008). Apart from that, the method of applying irrigation water also determines WUE. Conventionally, irrigation is done by surface irrigation methods like flood, border, check-basin, and furrow. These methods are very wasteful in terms of the amount of water applied. Therefore, many techniques and methods have been developed which can save irrigation water and, hence, enhance WUE. The irrigation management practices for enhancing WUE in the crops are discussed here in brief.

9.5.1 Critical Crop Growth Stage Approach

In case of limited availability of water for irrigation, farmers can apply irrigation at critical growth stages which are the most sensitive to moisture stress and can reduce yield loss (Kramer 1969). Yadav and others (2000) recognized critical growth stages in different crops corresponding to their water consumption (Table 9.5).

Table 9.5 Critical growth stages of selected crops corresponding to their water consumption

Crop	Critical growth stage(s)
Rice	Transplanting to tillering, panicle formation to flowering
Wheat	Crown root initiation (CRI), boot stage, milk stage, grain formation
Maize (kharif)	Silking
Maize (rabi)	Vegetative, booting
Pearl millet	Flowering
Pigeon pea	Flowering
Chickpea	Flower initiation, pod development
Soybean	Flowering
Sesame	Flowering
Mustard	Branching, siliqua development
Groundnut (kharif)	Pegging, pod development
Groundnut (rabi)	Vegetative, branching, flower formation, peg formation, pod growth
Sunflower	Vegetative, disc formation, flowering

Data source: Yadav et al. (2000)

9.5.2 Furrow Irrigated Raised Bed (FIRB) planting

In the FIRB technique, raised beds having 40–70 cm width and 15–20 cm height are made on which crop is planted. The furrow width is 25–30 cm. The dimensions of bed and furrow in the FIRB technique depend upon the type of crop (Jat et al. 2005). This method can save 25 to 40% of water than flat planting and thus improve WUE (Dhindwal et al. 2006).

9.5.3 Alternate Furrow Irrigation Method

In this method, water is supplied to the alternate furrows or only single side of the crop rows. As the water is applied in alternate furrows, the water loss through soil evaporation is decreased which increase the WUE than conventional every furrow irrigation method (Davies and Zhang 1991). This method saves about 25–50% water in comparison to each furrow irrigation that too with no penalty in crop yield (Golzardi et al. 2017). The method is appropriate for increasing WUE in arid as well as semiarid climates.

9.5.4 Micro-irrigation

Micro-irrigation method includes sprinkler irrigation (Figs. 9.5 and 9.6), drip irrigation (Fig. 9.7), micro-sprinklers, cablegation, surge irrigation, central pivot sprinkler irrigation, LEWA (Low Energy Water Application), and LEPA (Precision Application). Micro-irrigation methods can reduce irrigation cost, consumption of electricity, and fertilizer by 20 to 50%, 31%, and 7–42%, respectively (PMKSY 2015). The 'drip' system of irrigation is reported to decrease water use and increase crop yield by 30–60% and 20–50%, respectively, for several crops like sugarcane, cotton,

Fig. 9.5 Sprinkler irrigation. https://commons.wikimedia.org/wiki/File:Sprinkler_Irrigation_-_Sprinkler_head.JPG

Fig. 9.6 Central pivot sprinkler irrigation. https://www.goodfreephotos.com/united-states/colorado/other-colorado/center-pivot-irrigation-of-wheat-growing-in-yuma-county-coloardo.jpg.php

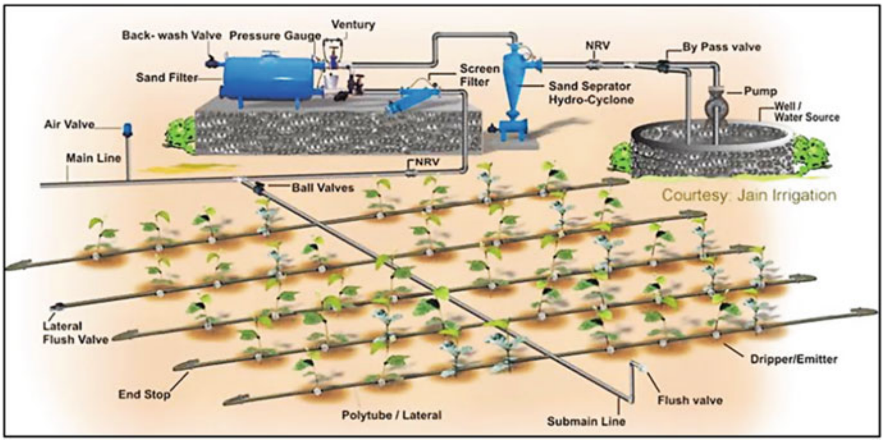

Fig. 9.7 Drip irrigation system. Source: Jain Irrigation Systems Ltd., Jalgaon

grapes (*Vitis* sp.), etc. (Indian National Committee 1994; Van der Kooij 2009). Sprinkler irrigation method can be adopted in the undulated areas where land leveling is not feasible. Drip irrigation is used when water is scarce. These micro-irrigation methods can enhance WUE in crops, particularly by saving irrigation water. Apart from increasing WUE, micro-irrigation methods are also known to improve fertilizer use efficiency (FUE) when applied through fertigation as shown in Table 9.6 (Ganeshamurthy et al. 2016). However, the farmers did not show interest in adopting these methods due to the high initial cost of the installment.

Table 9.6 Comparison of FUE under different application methods

Nutrient	FUE (%)		
	Soil application	Drip	Fertigation
N	30–50	65	95
P	20	30	45
K	50	60	80

Data source: Ganeshamurthy et al. (2016)

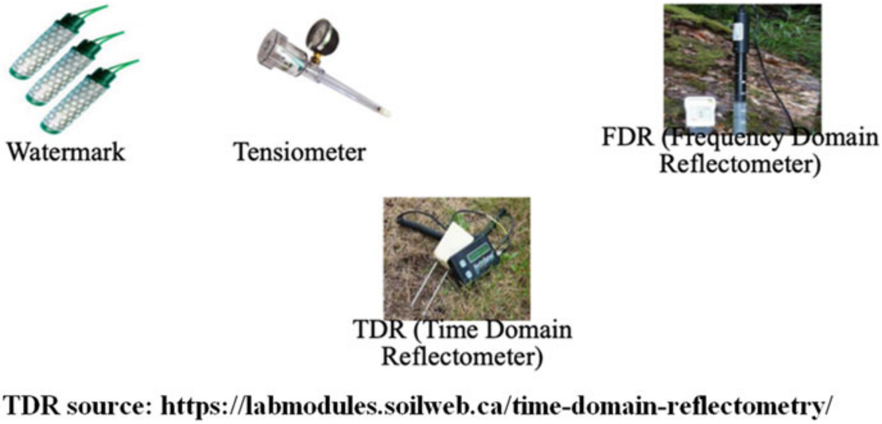

Fig. 9.8 Soil moisture sensors meant for scheduling the irrigation. TDR source: https://labmodules.soilweb.ca/time-domain-reflectometry/

9.5.5 Sensor-Based Irrigation

Irrigation scheduling is now possible with the help of soil-or plant-based sensors. Soil moisture sensors determine *in-situ* soil moisture content and irrigation can be applied when soil water content drops below a threshold value. There are various sensors to determine soil moisture, such as tensiometer, resistance block, Time Domain Reflectometer (TDR), neutron probe, Frequency Domain Reflectometer (FDR), watermarks, etc. which may be used for irrigation scheduling and precision irrigation (Francesca et al. 2010). TDR and FDR measure volumetric soil moisture content, while soil matric potential is measured by tensiometers and watermarks (Fig. 9.8). These soil moisture sensors are mainly useful for irrigation scheduling in field crops like wheat, rice, etc. In orchards, plant-based sensors are used for irrigation scheduling because trees have a deep-rooted systems and soil moisture sensors generally reflect the soil moisture status of surface soils. So, various plant-based sensors, such as sap flow meter, infrared thermometer, etc. which directly or indirectly measure the water status of the plant are used to schedule irrigation (Fig. 9.9). These sensors apply water based on the need of plant, so, they can effectively save irrigation water and improve WUE. However, technical knowledge about the operation of these sensors is required for scheduling irrigation.

Sap flow meter

Infrared Thermometer

Fig. 9.9 Plant-based sensors meant for scheduling the irrigation

9.5.6 Automated Smart Irrigation

The automated smart irrigation system automatically applies irrigation to the crops without the involvement of human labor in operating the water pump based on the crop's water demand, soil moisture content, soil temperature, air humidity, temperature, and weather forecast data from web service. This system uses various wireless sensors installed in the field and connected through the internet for collecting data on soil moisture content, soil temperature, air humidity, and temperature, etc. (Barman et al. 2020). This is known as IoT (Internet of Things)-based smart irrigation system (Fig. 9.10). This mainly works for pressurized irrigation systems like central pivot irrigation, sprinkler irrigation, drip irrigation, etc. which may be used in precision irrigation. This automated irrigation system controls the timing and quantity of water application through the decision-support system and control message is circulated through the wireless internet network. This irrigation system automatically gets switched on/off from remote areas which in turn decreases farmers' drudgery, saves time, water, energy, and labor (Subramani et al. 2020; Kumar et al. 2021). The WUE of this automated system is reported to be greater than 90% (Parameswaran 2016). In this way, automated smart irrigation system aids in site-specific or precision irrigation management, which minimizes water loss through evaporation, deep percolation, or runoff and increases crop yield resulting in higher WUE. However, the economic viability of this system in the present scenario is only for large farmers or corporate farming.

9.5.7 Mulching

The technique of covering the soil surface with things like crop residues, straws, plastic films, etc. is known as mulching. It is done to reduce evaporation from the

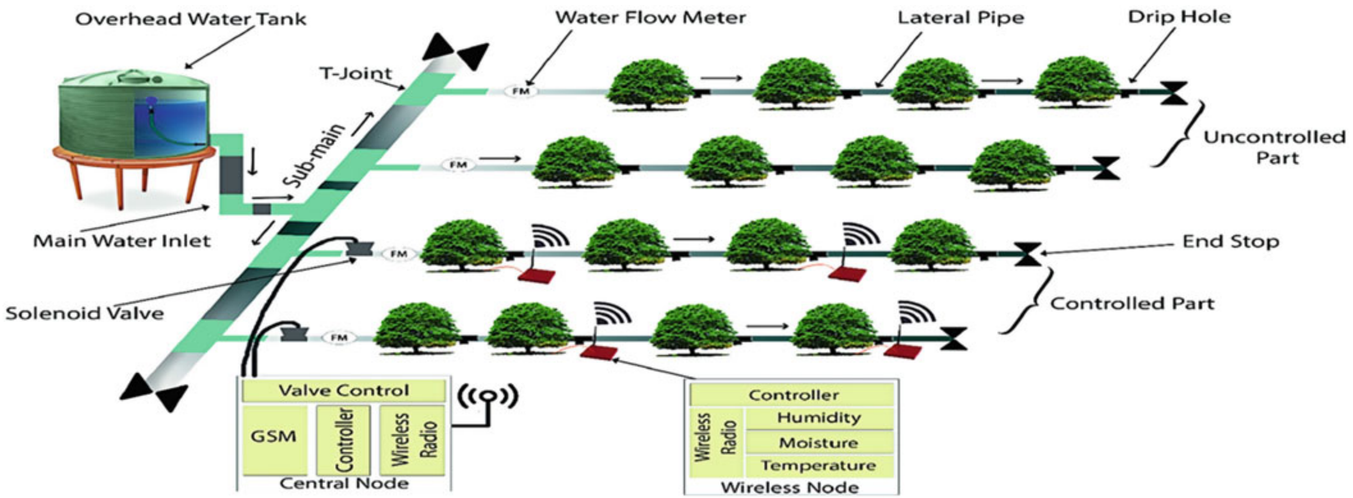

Fig. 9.10 Automated smart irrigation system. Source: Barman et al. (2020)

Table 9.7 Effect of different kinds of mulches on wheat grain yield and WUE

Treatments	Grain yield (kg ha^{-1})				WUE (kg ha^{-1} cm^{-1})	
	1st year	2nd year	Pooled	% increase over control	1st year	2nd year
Black polythene	3625	3785	3705	105.83	211.49	164.86
White polythene	3987	4048	4017	123.16	240.32	186.62
Paddy straw	2915	3020	2967	64.83	154.97	130.28
Forest leaf	2628	2709	2668	48.22	133.67	108.97
Control (No mulch)	1725	1875	1800	–	75.16	71.51
LSD (0.05)	10.53	7.32	–	–	–	–

Data source: Masanta and Mallik (2009)

soil, increase infiltration of water in the soil, moderate soil temperature variation, protect soil aggregates from the direct impact of falling raindrops, and reduce runoff and weeds infestation (Singh et al. 2014). Prihar et al. (1996) observed that there is a proportional reduction in the rate of evaporation with increase in the amount of surface crop residues. Crop residue or organic mulch can decrease the soil evaporation loss by 32–50% (Sauer et al. 1996; Chaudhary and Acharya 1993). Pandey et al. (1988) observed that grain yield and WUE can be significantly increased in the pearl millet crop under rainfed conditions by applying the straw mulch. Application of maize crop residue mulch improved the WUE in wheat by 51.1% than without mulch treatment (Rani et al. 2019; Kumar et al. 2020). Plastic mulch is another option for soil temperature moderation/increase and to retard evaporation from the soil, especially during the winter season to improve crop growth. In case of timely or late sown tomato (*Solanum lycopersicum*) crop, covering the soil with black plastic mulch enhanced the yield along with WUE than the crop cultivated in the absence of mulch (Rashidi et al. 2009). In another study by Das et al. (1995), water use decreased up to 24.2, 42.2, and 40% in gram, moong, and soybean, respectively which increased the WUE by 83.8, 85.8, and 74.9%, respectively, due to inter-row mulch treatments over control treatment. Similar results were recorded by Masanta and Mallik (2009) in wheat crop (Table 9.7). Plastic mulches are generally used for cash crops as they are expensive and create trouble during their removal or disposal. Vertical mulching is followed in black soils, also known as Vertisols, having high clay content and low infiltration capacity. Here the crop residues are packed in trenches having the size of 30 × 60 cm^2 excavated at 5–10 cm intervals for increasing the infiltration rate and water intake capacity. Mulching is found suitable for low and medium rainfall regions to save soil moisture.

9.5.8 Tillage Practices

Tillage practices have a direct bearing on soil physical properties like infiltration, soil structure, and aggregation, soil pores distribution, soil aeration, the motion of soil

Table 9.8 Effect of different tillage practices on physical properties of soil

Treatments	BD (Mgm^{-3})	Porosity (%)	AWC (%)	WSA (%)
Minimum tillage	1.36	48.97	44.50	60.04
Two harrowing	1.38	47.24	43.33	58.78
Harrowing + pulverization	1.39	47.48	43.88	59.22
Conventional tillage	1.37	47.01	42.75	53.32
Farmers practices	1.41	46.69	41.60	63.82
Barren land	1.39	47.47	43.78	53.24
LSD	0.04	1.45	10.24	0.06

Data source: Kumar et al. (2020)

water and dissolved nutrients, soil temperature, mechanical impedance, bulk density (BD), available water capacity (AWC), water-stable aggregates (WSA), etc. Some of the soil physical properties affected by tillage are presented in Table 9.8. It aids in suppressing weeds infestation, soil-borne diseases, and other insect pests. Tillage affects WUE by modifying the hydrothermal conditions of soil which influences root proliferation and canopy development of the crop. Tillage practices are of various types like conventional tillage, conservation tillage, deep tillage, shallow inter-row tillage, off-season tillage, etc. The selection of tillage practice is done based on climatic conditions, soil type, and cropping system. Shallow inter-row tillage breaks the soil crust, discontinues the capillary pores, and closes the soil cracks which minimize the short-term direct soil moisture loss through the evaporation process. Deep tillage up to 30–45 cm depth at 60–120 cm space intervals is practiced occasionally to break the hard-pan formed in the subsoil. Deep tillage at the interval of 3–4 years after crop significantly improvises the infiltration and moisture storage capacity of the soil, which enhances the WUE (Bhan 1997). However, the benefits of deep tillage are found only in deep-rooted crops in high rainfall years.

Conservation tillage, which involves zero or no-tillage, minimum tilth, mulch retaining tillage, ridge tillage, contour tillage, and permanent bed system aims toward minimal disturbance of soil along with retention of crop residues, comes under the domain of CA. CA is nowadays promoted within and outside the country by scientists and researchers to increase WUE besides additional gains, such as saving of cost, fuel, energy, and labor, Soil Organic Carbon (SOC) sequestration, improvement of soil quality, and protection of natural resources, which is essential for achieving agricultural sustainability (Busari et al. 2015). It has been reported that zero-tillage (ZT) can save approximately 20–35% of water (irrigation) in wheat in comparison to conventional tillage (CT) (Gupta et al. 2002). Jat et al. (2013) while working in light-textured soils found higher WUE (16%) in maize and wheat crops when grown on beds that were permanent and raised when compared to conventional bed systems. In pigeon pea–wheat cropping system, CA resulted in more WUE compared to CT (Das et al. 2016). Conservation tillage is found to reduce the evaporation loss by 23–37% than CT in North-western Indo-Gangetic plains while increasing the WUE (Parihar et al. 2019).

9.6 Techniques for Enhancing Nutrient Use Efficiency (NUE)

Despite increased amounts of fertilizer nutrients applied to a crop, only a small amount of it along with some native soil nutrients, are being utilized by the crops, particularly in intensive cropping, where 2–3 crops are being taken in a year. Also, the usage of chemical fertilizers is not always a wise alternative before the large number of poor farmers living in a variety of regions worldwide. This statement bears the reason as many such farmers cannot afford to pay for fertilizer inputs. Nevertheless, there is a need to enhance NUE while maintaining the soil's physical conditions. NUE is comprised of three key components: Uptake Efficiency (UpE), Utilization Efficiency (UtE) in biomass production; and Harvest Index (HI) (Ciampitti and Vyn 2012). UtE and HI can be represented as a single component, i.e., utilization efficacy for reapable products. The techniques for enhancing NUE are briefly discussed below:

9.6.1 Balanced Fertilization

Foodgrain production in India has risen from 55 Mt. to 285 Mt. whereas the fertilizers consumption has risen from 0.07 Mt. to 27 Mt. (Fertilizer Association of India 2011) during the period of 1950–1951 to 2018–2019, indicating a very poor FUE (Prasad 2009). Applications of N fertilizer in large quantities have shown the linkage with deteriorating soil physical condition and groundwater quality, especially due to nitrate form posing health hazards. Further, the gaseous losses of N as NH_3 and NO_2 during N fertilization have adverse effects on the environment. Excess N application than crops' N demand results in excessive crop growth which increases the susceptibility of crops to diseases and lodging along with the increase in the potential for nitrate-N leaching. Therefore, the major part of fertilizer N (about 60–70% of recommended) have to be supplied during the critical growth stage of the crop to synchronize the N supply with crop demand (Cui et al. 2008).

In addition to N, P, and K macro-nutrients are also required by the cereal-based systems. P and K deficiencies are becoming pervasive in regions where deficiencies were not present earlier. This is due to high cropping intensity, increasing erosion of topsoil by runoff water, and the prevalence of year-round irrigated production systems. It is estimated that about 50% of the districts in India are classified to be "low" in extractable P (Desai and Gandhi 1990), due to the increased focus on the application of N in place of balanced doses of fertilizers required to sustain the soil fertility. This unbalanced fertilizer application resulted in the decline of FUE (Table 9.9).

9.6.2 Selection of Crop and Variety

Crop species vary significantly in the growth period from planting/sowing unto harvest, having the shortest of 21 days for baby spinach leaf (*Spinacia oleracea*)

Table 9.9 Effect of nutrient management on agronomic efficiency of nitrogen (AEN)

Crop	Percentage increase in agronomic efficiency of nitrogen	Agronomic efficiency of nitrogen (kg grain kg^{-1} N)		Nitrogen application (kg ha^{-1})	Yield in control plot yield (t ha^{-1})
		Nitrogen application alone	NPK application		
Wet season rice	100	14	27	40	2.7
Summer rice	671	11	81	40	3.0
Maize	100	20	39	40	1.7
Pearl millet	219	5	15	40	1.1
Sugarcane	189	79	228	150	47
Sorghum	126	5	12	40	1.3
Wheat	85	11	20	40	1.5

Data source: Prasad (1996)

to the longest of 270 days for the wheat. Within crop species, for instance, late-maturing cultivars of potatoes have physiologically a prolonged period of crop growth. Simultaneously, this longer period is necessary to extend the root system and more uptake of N to produce increased biomass (Iwama 2008). Nevertheless, a shorter growth period cannot always be related to a low N demand. Sometimes short-term crops, like spinach require high N application to produce high yields in a short time. Therefore, one should be very careful while selecting the crop taking into account the crop growth durations, mean root depth, recommended dose of fertilizers, mean yield, and harvested N.

To enhance the NUE, farmers need to select those varieties which have high agronomic NUE (AgNUE), i.e., the varieties which can produce high harvestable biomass for each unit nutrient applied through fertilizer. The NUE is also dependent on the physiological mechanisms traits of the crops. They may be, root architecture, nutrient uptake by each unit length of roots, leaf aging, and remobilization of nutrients in the crop (Malagoli et al. 2005; Gewin 2010).

9.6.3 Intercropping

Intercropping of cereals and legumes often gives higher resource use efficiency (NUE and WUE) in comparison to solo crop cultivation (Ofori and Stern 1987). Intercropping of crop species that have different times for their maximum nutrient demands and other input resources may prolong the period of resource utilization (Chandra et al. 2011). Due to differential utilization of inputs like fertilizers by main and intercrop, fertilizers may be used more efficiently when compared with sole cropping increasing the yield (Jensen 1996). Further, a cereal–legume intercrop is more useful because constituting crops may be able to use varying N-sources (Chu et al. 2004). The cereal crops, generally are more exhaustive in comparison to legumes for inorganic N of the soil, whereas the pulse crops can fix atmospheric-N symbiotically with the help of soil Rhizobium. This type of relationship between crops is of special importance in farming systems having low-input use. Moreover, two crops varying in tallness, canopy cover, adaptability, and growth habits, grow at the same time with the lowest competition, higher stability of yields over varying seasons, and better use of nutrients, water, and land resources (Bhatti et al. 2006).

9.6.4 Integrated Nutrient Management (INM)

The overall principle of INM is to enhance crop yields per unit area along with the efficacy of resource utilization through the integrated application of nutrients. Fertilizers, organic manures, green manuring, pulse crops, crop residues, wastes from industries, sewage-sludge, etc. are the main components of INM. Here, we try to manage the supply of plant nutrients in the rhizosphere at a rate that matches the amount of crops' nutrient requirement and further matches with time/stage of crop growth and is integrated with space to meet crop nutrient requirements. The nutrient content of some of the organic manures is given in Table 9.10. Organic manures having a significant residual effect on the succeeding crops besides supplying plant nutrients to the existing crop. The long-term experiments (LTEs) which are being undertaken by the All India Co-ordinated Research Project (AICRP) on Integrated Farming Systems (AICRP-IFS 2011) revealed that Farm Yard Manure (FYM) can replace some portion of fertilizer N requirement of rice in a rice–wheat system giving

Table 9.10 Average nutrient composition of some organic manures/wastes

Category	Source	Nutrient content (%)		
		N	P_2O_5	K_2O
FYM/composts	Farmyard manure Poultry manure	0.5–1.0	0.15–0.20	0.5–0.6
	Urban compost	2.9	2.9	2.3
	Rural compost	1.5–2.0	1.0	1.5
	Vermi compost	0.5–1.0	0.2	0.5
		1.27	0.50	0.19
Animal meals	Horn and hoof	13.0	0.3–0.5	-
	Fish	4–10	3–9	1.8
	Raw bone	3–4	20–25	-
Animal wastes	Cattle dung	0.3–0.4	0.10–0.15	0.15–0.20
	Cattle urine	0.80	0.01–0.02	0.5–0.7
	Sheep/ goat droppings	0.65	0.50	0.03
	Night soil	1.2–1.5	0.8	0.50
Oil cakes	Castor	5.5–5.8	1.8	1.0
	Coconut	3.0–3.2	1.8	1.7
	Neem	5.2	1.0	1.4
Biogas slurry	–	0.98	0.66	0.14
Sewage sludge	–	0.97	0.27	0.11

Table 9.11 Effect of integrating organics and inorganic fertilizers on crop productivity

Integrated nutrient application		Economic yield (t ha^{-1})		
Rice	Wheat	Rice	Wheat	System
Banaras				
N + P + K	N + P + K	4.33	3.67	8.00
50% RDF of NPK + 50% N (FYM)	N + P + K	4.71	4.02	8.72
75% RDF of NPK + 25% N (FYM)	75% N + P + K	4.39	3.75	8.14
Kanpur				
N + P + K	N + P + K	4.35	4.44	8.78
50% RDF of NPK + 50% N (FYM)	N + P + K	4.31	4.51	8.83
75% RDF of NPK + 25% N (FYM)	75% N + P + K	4.10	4.33	8.43
Kalyani				
N + P + K	N + P + K	3.51	2.26	5.77
50% RDF of NPK + 50% N (FYM)	N + P + K	3.97	2.68	6.65
75% RDF of NPK + 25% N (FYM)	75% N + P + K	3.72	2.32	6.04
Jabalpur				
N + P + K	N + P + K	5.62	3.35	8.97
50% RDF of NPK + 50% N (FYM)	N + P + K	5.58	3.30	8.88
75% RDF of NPK + 25% N (FYM)	75% N + P + K	4.86	2.81	7.67
Ludhiana				
N + P + K	N + P + K	6.14	5.14	11.29
50% RDF of NPK + 50% N (FYM)	N + P + K	6.43	5.39	11.82
75% RDF of NPK + 25% N (FYM)	75% N + P + K	6.54	5.25	11.79
Sabour				
N + P + K	N + P + K	4.66	4.13	8.80
50% RDF of NPK + 50% N (FYM)	N + P + K	5.22	4.75	9.96
75% RDF of NPK + 25% N (FYM)	75% N + P + K	4.85	4.33	9.18

Data source: AICRP-IFS (2011)

annual yields either equal to sole recommended fertilizer application or a bit higher by following INM package (Table 9.11). The partial factor productivity of nitrogen (PFPN) in these LTEs, showed a marked increase in the INM treatments compared with the application of recommended dozes of NPK fertilizers.

Applying only the organic materials cannot be adequate to sustain crop yields as the quantity as well as mineralization from these resources is limited (Bayu et al. 2006). The combination of organic and inorganic N sources can retard the losses of N by changing the mineral N into organic substances, and therefore, can increase the efficacy of inorganic fertilizers in comparison to the use of fertilizer N alone (Yang et al. 2015). This integration can increase the efficiency of nutrient uptake by crops (Han et al. 2004), and improve carbon management index carbon pool index, and liability index of the soil (Fig. 9.11), which in turn improve the physical environment of soil (Kumar et al. 2019). A similar result was observed by Ke et al. (2017), who reported that integration of inorganic N with organic manure (83.3%:16.7%) showed higher nitrogen use efficiency in comparison to the alone application of inorganic Nitrogen this is due to the comparatively uniform and gradual release of N from organic fertilizers.

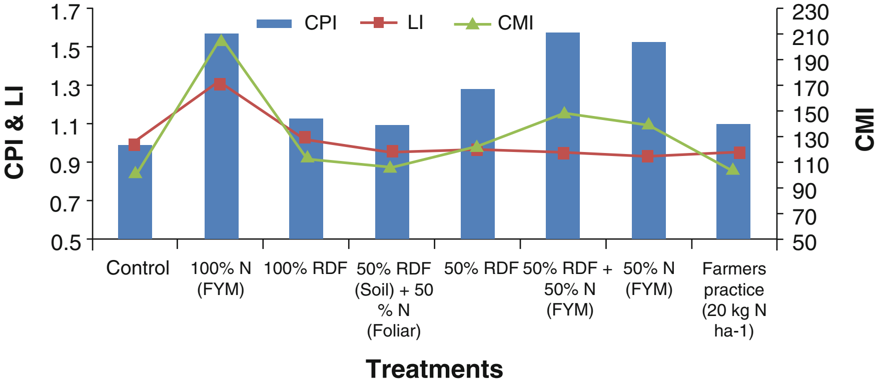

Fig. 9.11 Carbon Pool Index (CPI), Carbon management Index (CMI), and Liability Index (LI) of soil affected by different fertilizer management practices. Data source: Kumar et al. (2019)

9.6.5 Addition of Organic Matter

Soil Organic Matter (SOM) plays an important regulatory role in the complex buffering processes of soil. Organic matter application not only upgrades the soil's physical properties (Zou 2018) but also stimulates microbial activity, thus hasten the process of SOM decomposition (Kuzyakov 2000). In general, both the form and provenance of N-fertilizers, influence grain yield by controlling N conversions, altering the N-loss patterns, and affecting NUE (Abbasi 2013). Application of SOM not only augments soil N content, but also increases the SOC sequestration, and affects the soil pH and BD (Afreh et al. 2018; Shi et al. 2019). Moreover, the long-term application of SOM concomitantly enhanced soil quality and formed a firm base for encouraging soil sustainability (Liang 2013). In the comparison of only inorganic fertilizer applications, the integrated use of organic manure and fertilizer improved the crop productivity in the experimentations and increased the SOC and N content (Gai et al. 2018; Lollato et al. 2019). Thus, the integrated use of manures and fertilizers has been commonly recommended (Chivenge et al. 2011).

9.6.6 Conservation Agriculture

CA ensures to maintain a constant residue cover on the soil surface, minimum possible mechanical disturbance of soil, and crop rotation and crop diversification. It augments the soil biodiversity and innate biological processes in and above the soil, thus improve resource (nutrient and water) use efficiency and sustained production of crops. The principles of CA are invariably relevant to all cropped landscapes and land uses and can be integrated with local practices. Aulakh et al. (2012) reported that N uptake was reduced by 3–5% under CA in the winter-grown wheat crop as compared to that of conventional agriculture. Use efficiency of the majority of the nutrients was significantly increased by the adoption of CA in the maize–horse gram (*Macrotyloma uniflorum*) cropping system in Alfisols (Kundu et al. 2013). Thus, CA is useful in enhancing both NUE and WUE, besides its other multiple benefits in the agriculture system.

9.6.7 Application of Novel Fertilizers

Novel fertilizers materials like nano-fertilizers, foliar spray fertilizers materials, aqueous fertilizers for fertigation have come up with a great potential of increasing NUEs. Earlier it started with slow-release fertilizers (SRFs) like neem coated urea and few others. SRFs are deliberately designed products that release the active plant nutrients in a regulated manner to match with the time/stage-bound needs of crops for nutrients, and thus provide higher NUE along with better yields (Shaviv 2005) (Table 9.12). An ideal SRF is generally coated with some natural or quasi-natural, environmentally safer, macromolecule substance that reduces nutrient delivery to such a steady rate that one-time application to soil could cater to the nutrient needs of particular crop growth (Blouin 1967). The term, controlled-release fertilizer (CRF), is generally taken analogous to SRF. However, Shaviv (2005) and then Trenkel (2010) defined the differences between both forms. In SRFs, the nutrient release pattern is almost unpredictable and persists subject to variations in the type of soil and climate whereas in CRFs, the release pattern, release time and amounts, are predictable, within limits. Literature relates the history of development and evolution of CRFs' to the early 1960s (Blouin 1971). Initially, sulfur and polyethene were used for coating the fertilizer materials to prepare SRFs. Later on, many polymer materials, organic-coating substances, and even nano-sized composite materials were included.

Different carrier materials are being used that are suitable for the nutrients *viz* hydroxyapatite NPs, nanoclays, mesoporous silica, polymeric nanoparticles (NPs), carbon-based nanomaterials, and other nanomaterials. Nanoclays are suitable as nutrient carriers with the ability to provide physical barriers due to structural design to safeguard nutrient molecules (Roshanravan et al. 2014; Songkhum et al. 2018)

Table 9.12 Slow-release urea forms to improve the N use efficiency

Fertilizer forms	Example
Nitrification inhibitors	Nitrapyrin, Acetylene. 2-amino-4-chloro-6-methyl-pyrimidine (AM), Dicyandiamide (DCD),Encapsulated Ca-carbide, ATC (4-amino 1,2,4-triazole), DMPP (3–4-dimethylpyrazole phosphate), neem cake, karanj cake
Coated with urease inhibitors	Hydroquinone, phenyl phosphorodiamidate (PPD)
Enlargement of the granule	Granular urea, Supergranule of Urea,
Limited soluble urea forms	Urea form, Oxmide, Urea-Z
Coated with inert material	Coated with a polymer, sulfur, rock phosphate, lac, gypsum, and neem cake

and the ion exchange provide the insertion of nutrients into nanoclay layers (Everaert et al. 2016; Benício et al. 2017; Songkhum et al. 2018). These two characteristics of nanoclays have the potential to provide nutrients for a longer duration (Pereira et al. 2012; Benício et al. 2017; Songkhum et al. 2018). Hydroxyapatite nanohybrid is considered a potential nano-enabled material for the slow liberation of N (Kottegoda et al. 2017). Hydroxyapatite [$(Ca_{10}(PO_4)_6(OH)_2)$] is a biocompatible substance that is naturally present in human and animal hard tissues which possess a high ratio of surface area to volume, that provide the ability to deliver Ca and P. Another carrier mesoporous silica has a good capacity of adsorbing urea (upto 80%) and produced a slow-release pattern into the water as well as soil (5-times increase in release period in comparison to pure urea) (Wanyika et al. 2012). The carbon-based nanomaterials too showed that Cu NPs-loaded carbon nanofibers slowly released Cu in water as compared to Cu-loaded activated carbon microfibers (Ashfaq et al. 2017). A test made on germination of gram seed revealed that nanofiber-based formulations increased, the capacity of plants for water uptake, rate of germination, and contents of protein and chlorophyll.

9.6.8 Fertigation

In fertigation, fertilizer material is dissolved in water and applied with irrigation water through the micro-irrigation systems like drip and sprinklers. The fertilizers needed by the crops are applied to the soil directly by dissolving into the irrigation water, surrounding the active root zone of the crop. This method of irrigation provides a quite effective way to regulate the placement, time of application, and kind of fertilizer required as per the fertility status of soil and stage of crop growth. This technology improves the NUE by reducing nutrient losses through the processes of volatilization, nutrient leaching, and soil fixation. Therefore, fertigation provides similar conditions to the hydroponics in the soil, if managed properly.

9.6.9 Precision Nutrient Management

Precision nutrient management is the science of employing modern, innovative, and site-specific technologies for supplying nutrients to the soil considering the spatio-temporal variability in the crop field. Every field has spatial heterogeneity which is identified by the use of optical sensors, chlorophyll meter, green seeker, leaf color chart, omission plot technique, and crop models like Nutrient Expert (NE) and QUEFTS model for need-based nutrient application in the crops. This can facilitate farmers to use the inputs more efficiently and derive more return per unit of input used. Following tools are used in precision farming.

1. Global positioning system (GPS)
2. Geographical information system (GIS)
3. Grid sampling

4. Variable-rate technology
5. Yield monitors
6. Yield maps
7. Remote sensors
8. Auto-guidance systems
9. Proximate sensors
10. Computer hardware and software

The spatial variability in the field can be managed through GIS and GPS technologies. GPS is linked to the field monitors to provide field maps. These maps are further useful in regulating VRCT (Variable Rate Chemical Applicators) and VRS (Variable Rate Seeders). This helps in site-specific fertilizers application considering the spatial soil variability which reduces fertilizer dose and enhances NUE (Table 9.13). Kaur et al. (2020) reported that site-specific nutrient management with Nutrient Expert and Green Seeker enhanced the agronomic and recovery use efficiency of N.

9.7 Conclusion and Future Perspective

Managing soil physical health is as much important as chemical and biological health for sustainability and higher productivity levels. This demands site-specific technologies viz. optimum tillage practices, mulching, use of suitable cropping pattern, compaction of loosely bound (sandy) soils, amendment of acid and salt-affected soils, amelioration of soil physical constraints, efficient use of organic manures and fertilizers, and conservation agriculture, inter-cropping which can upgrade the soil physical environment. Such a soil environment improves the transmission of water, air, and heat through the soil and thus enhances the water and nutrient availability, uptake, and use efficiency of these two vital resources. Enhanced efficiency of water and nutrients stands as the major target of the present scenario to deal with the diminishing resources in agriculture due to population pressure, soil degradation, and diversion of agricultural lands and inputs for other purposes. There are several tools and technological options available that can help farmers to increase input use efficiency (water and nutrient) at the farm level without compromising the soil health and quality along with maintaining the optimum yield of the crops. The input use efficiency can be enhanced by techniques as discussed above and further by appropriate irrigation scheduling, micro-irrigation, slow-release fertilizers, nano fertilizers, etc. Enhancement in NUE is possible by the balanced use of N, P, and K fertilizers in crops along with more judicious water management. The advanced and novel technologies for water and nutrient management, i.e., automated smart irrigation and precision nutrient management, etc. are very useful technologies but are scarcely adopted in developing countries like India, due to the high cost of their installation and operation as well as the requirement of good technical knowledge for their operations. However, research is going on to make these precision management technologies economical and farmers friendly in

Table 9.13 Some studies on site-specific N fertilization application in different wheat species

Wheat species	Study sites	Approach	Effect on yield and NUE	Reference
Durum wheat	Foggia (Italy)	The N Application rate split based on the management zones (high, medium and low yielding)	High-yielding area had the highest monetary return and least nitrate leaching by annual application of N @ 90 kg ha^{-1}. Low-yielding area had little money returns for applying N more than 30 kg ha^{-1}	Basso et al. (2009)
Winter wheat	Oklahoma (USA)	In-season top dressing to obtain the highest yield	Reduction (59–82%) in overall N level, based on the site	Biermacher et al. (2006)
Winter wheat	Potsdam (Germany)	Varied application of fertilizer according to wheat plant biomass, indirectly measured by a mechanical sensor-pendulum meter	Decrease 10–12% fertilizer application without yield reduction and quality grain.	Ehlert et al. (2004)
Winter wheat	North China Plain	Sensor-based N management strategy	NUE were 61.3 and 13.1% for the sensor-based management strategy and farmers practices, respectively. Leftover N content of the soil from sensor-based and farmer N management strategies was 115 and 208 kg N ha^{-1}, respectively. Apparent loss of N was 4 which is much lower than the farmers practice (205 kg ha^{-1})	Li et al. (2009)

developing countries. Still, the farmers of developing countries have ample opportunities available to enhance WUE as well as NUE and manage soil physical constraints by adopting various agronomical measures and application of suitable fertilizers or soil amendments as discussed in this chapter. Therefore, the cultivators should be encouraged to adopt these technologies/practices of judicious soil management, so that increased use efficiency of the water and nutrient inputs may be attained toward higher and sustainable food production while saving our natural resources.

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Input Use Efficiency for Improving Soil Fertility and Productivity

10

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Abstract

Soil, water, nutrients, agrochemicals, and energy are important natural resources and as well as agricultural inputs needed to sustain global food production. The overexploitation and irrational supply of these farming inputs to intensify the crop production is an alarming issue for the farming communities, policymakers, and scientists as it is difficult to manage the input use efficiently without compromising the productivity and environmental as well as economic security. The precision supply of crop need-based inputs viz. water, nutrient, and energy in right time, right amount, right way, and from right sources is a need of the hour. This chapter is focused on efficient management practices with respect to soil and crop management practices and technological interventions aimed toward soil and environmental sustainability. Climate-resilient practices, crop residue management, conservation agriculture, sustainable land management, vertical farming along with modern nanotechnology-based input management is also well discussed in this chapter.

Keywords

Soil quality · Intensive agriculture · Climate-resilient · Conservation agriculture · Crop residue · Nutrient management

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Abbreviations

AFOLU	Agriculture, forestry and other land use
Al^{3+}	Aluminum ion
AMF	Arbuscular mycorrhizal fungus
As	Arsenic
C	Carbon
C: N	Carbon:nitrogen ratio
Ca	Calcium
CH_4	Methane
Co	Cobalt
CO_2	Carbon dioxide
Cu	Copper
FAO	Food and Agriculture Organization
FYM	Farm yard manure
GHGs	Green house gases
INM	Integrated nutrient management
IPCC	Intergovernmental Panel on Climate Change
IPNS	Integrated plant nutrient supply system
Mg	Magnesium
Mha	Million hectares
Mn	Manganese
N	Nitrogen
N_2O	Nitrous oxide
Na^+	Sodium-ion
NH_3	Ammonia
NH_4^+	Ammonium
Ni	Nickel
NOP	National organic programme
O	Oxygen
P	Phosphorous
Pb	Lead
S	Sulphur
SCMS	Soil and crop management strategies
SLM	Sustainable land management
SOC	Soil organic carbon
SOM	Soil organic matter
SPAD	Soil plant analysis development
SSNM	Site-specific nutrient management
Zn	Zinc

10.1 Introduction

Adoption of high yielding varieties along with the expansion of water availability and enhancement of chemical fertilizers and other agrochemical use has brought about the tremendous increment of crops yield to cope up with the food demand of continuous increasing human population (Garai et al. 2020). The crop production is basically a complex interaction of natural resources with external inputs and the new era of agriculture demands the efficient input use and resource conservation to ensure the pace of crop production sustainably without hampering the soil inherent fertility (Panwar et al. 2018). However, in the recent era, the injudicious use of chemical fertilizers and repeated cultivation of major cereals facilitates to excess soil nutrient mining and productivity fatigue (Shweta and Malik 2017). The rice–wheat cropping system is considered as the predominant lifeline for most of the Asian population, occupying 24 Mha occupying 24 Mha areas in South Asian countries (India, Bangladesh, Nepal, Pakistan, and China) (Singh et al. 2013). The capital and energy-intensive agriculture production system without concerning the input use efficiency puts this lifeline of human beings on a ventilator (Panwar et al. 2018; Kumar et al. 2018). External application of fertilizers meets ~50.8% of N demand of rice and wheat, indicates in poor nutrient use efficiency (Ravisankar et al. 2014). In highly productive areas, more particularly in the Indo-Gangetic plains of India, nutrient mining is the most serious concern (Singh et al. 2008a, b). Yield stagnation, poor input use efficiency, deterioration of soil organic carbon, multi-nutrient deficiencies, soil degradation, and lowering factor productivity questioned the system sustainability. Additionally, farming activities occupy 80% of total available freshwater and it has been estimated that the per capita water availability will decrease from 1820 m^3 $year^{-1}$ to 1140 m^3 $year^{-1}$ within 2001–2050 in India (Mahato 2014). The overextraction of groundwater resources and irrational application of irrigation without concerning the actual crop need, put the agriculturally developed countries into high water scarcity, marked as "dark zone" (Mondal et al. 2020a). As an example, e northern and eastern India are demarcated as major hotspots of water resource depletion as heavy irrigation demands in rice--wheat cropping system (Garai et al. 2020). Furthermore, the post-monsoon fallow land lowers the use efficiency of residual soil moisture and nutrients (Singh et al. 2016; Kumar et al. 2020). The use of heavy machinery in modern agriculture deteriorates the soil structure and nutrient retention capacity (Saharawat et al. 2010).

Therefore, the efficient input use efficiency to maintain the soil fertility and productivity should be taken into consideration and can be achieved by assessment of precise crop demand, conservation against possible losses, and integrated nutrient management in a synergistic way and the proper distribution of inputs among the competing demands. The conservation agriculture, climate-smart strategies, organic farming, and diversity of cropping system would be beneficial to enhance the land productivity and fertility in long term (Panwar et al. 2018). Likewise, the mixture of chemical fertilizer with organic manure increases 24% of soil organic carbon even in rice--wheat mono-cropping system (Majumder et al. 2008). Yield enhancement due to better soil fertility as a consequence of balanced fertilization is revealed in the previous literature (Shukla et al. 2009). Actually, balanced nutrition is enhanced by the nutrient absorption ability in requisite amount by plants. Additionally, the split application and need-based nutrient supply should be tailored to harness the maximum nutrient use efficiency of applied nutrients (Buresh et al. 2010). Most importantly, the adoption of conservation agriculture, such a, minimum soil disturbance, soil cover, and avoiding the heavy machinery not only maintains the soil ecological sustainability but also result in better productivity than conventional practices. Moreover, the precision agricultural tools like variable-rate fertilizer application, precision irrigation in a pressurized system, laser land leveller (Humphreys et al. 2010; Kumar et al. 2021), site-specific nutrient management (Buresh et al. 2010), real-time nutrient application, leaf color chart (Ramesh et al. 2016), and crop modeling (Das et al. 2009) facilitate to low-input demand with maximum efficiency (Buresh et al. 2010). This chapter includes comprehensive information of global food demand, modern farming practices, their constraints, and sustainable way to improve nutrient use efficiency without compromising the crop productivity.

10.2 Trends of Increasing Food Demand by Growing Population in Future

Food security is a big challenge that mainly depends on the agriculture sector to meet the food demand in near future. This concern is mainly due to the fact that approximately 9.05 billion people's food demand is accomplished by agriculture (Pollock et al. 2008). Beside this, it is responsible for different services, i.e., water purification, management of waste for the production of fuel, fibre; maintaining the biodiversity and finally balances the environmental security (Sayer and Cassman 2013; Meena et al. 2020). In recent era, the increasing trend of population, continues growth of income per person and rapid urbanization demands more diversified food. It has been estimated that the urbanization will increase from 49% in 2009 to 70% in 2050 (FAO 2009) which alter the food consumption patterns. The projection of rising global food demand is directly proportional to increasing consumer incomes in developing countries. Interestingly, the trading activities have also equal importance to meet this higher demand which aggravates the crisis more (FAO 2009).

According to World Bank, it is estimated that global annual income increases of 2.9% between 2005 and 2050, where 1.6% for high-income countries and 5.2% for developing countries (van der Mensbrugghe et al. 2009). An increment of global output from 20% to 55% in the years between 2005 and 2050 has been pointed out by World Bank (van der Mensbrugghe et al. 2009). Global agri-food demand in 2050 is projected to be much higher than 2007 which is greater than the growth in global population Fig. 10.1. Current enhancement of 31 million Mg year^{-1} will not meet the future food requirement of 43 million Mg year^{-1} that needs a 39% increase in food grain production. Average 0.8% and a minimum of 1.8% in the least developing countries agricultural production per year have to be increased to compensate population growth (van der Mensbrugghe et al. 2009). With the modern

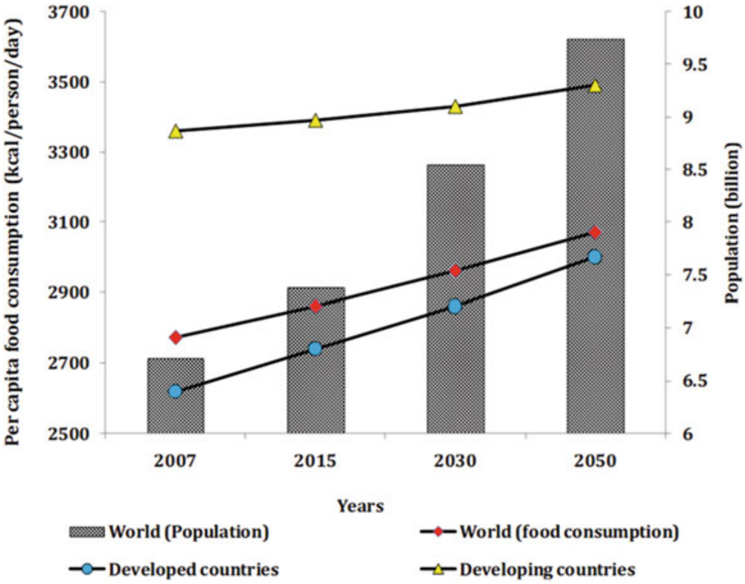

Fig. 10.1 Trend of future population and food demand (Source: FAO 2009)

package and practices that include improved machinery and external inputs it is now possible to cultivate the large area with improved varieties, efficient water technologies which in turn increases the yield (Tester and Langridge 2010). Therefore, overall improvements in crop production fulfill the yield requirement in a sustainable way (Zhang et al. 2014).

Thus, maximum emphasis should be givento maximize system productivity along with low environmental pressure as no single way can mitigate the nutritional demand of the ever-rising population. Changes are needed in the production, postharvest storage, food processing, and their distribution as an evolutionary approach, such as green revolution to fulfill the future food demand (Godfray et al. 2010). According to the United Nations Food and Agriculture Organization, more than double net imports of cereals will be done by developing countries by 2050 (FAO 2009). As per the projection, Asian countries would be the pioneer to increase the real value of global agri-food demand (Fig. 10.2), in which India will exclusively account 13% of demand (FAO 2009). The food demand by India also accounts the highest value in case annual average growth rates (1.9% year^{-1}), followed by China (1.8%year^{-1}).

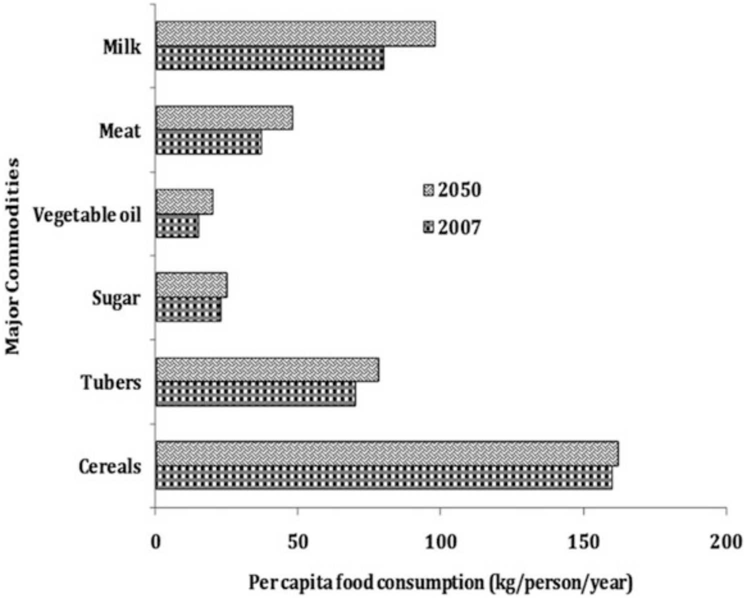

Fig. 10.2 The world agri-food demand for major commodities (Source: FAO 2009)

10.3 Intensive Agriculture with Modern Technologies Deteriorating Soil Health

Soil is a dynamic, living resource vital for food and fiber production and balanced ecosystem functioning to maintain the sustainability of life on earth (Doran et al. 1996). It provides physical support, chemical, and biological support for plant growth and numerous living organisms both micro and macro flora and fauna (Doran et al. 1996; Tripathi et al. 2020). The quality of soil is a determining factor of farming system sustainability and environmental viability that would significantly maintain the plant, animal, and human health as well (Garai et al. 2020; Yadav et al. 2020). Comprehensively, soil health refers to the potentiality of soil to function as a crucial living system in accordance with the changes in its properties over time due to human interference or natural events. The soil health encompasses a good balance among the physical, chemical, and biological conditions of soil and their interactions (Fig. 10.3). A good balance among the physical, chemical, and biological aspects of soil health determines how efficient the soil is. Healthy soils are the key factor to help in better crop production, food and nutritional security, and facilitate to withstand in climatic abnormalities along with the improved resilience to extreme stress. Yet, an invisible threat is putting soils and all that they offer at risk (FAO 2018a, b).

In order to secure food requirement for the ever-rising population of the world, urgency is there to increase food production from the shrinking agricultural area. With the advancement of science and technology several new methods of agriculture

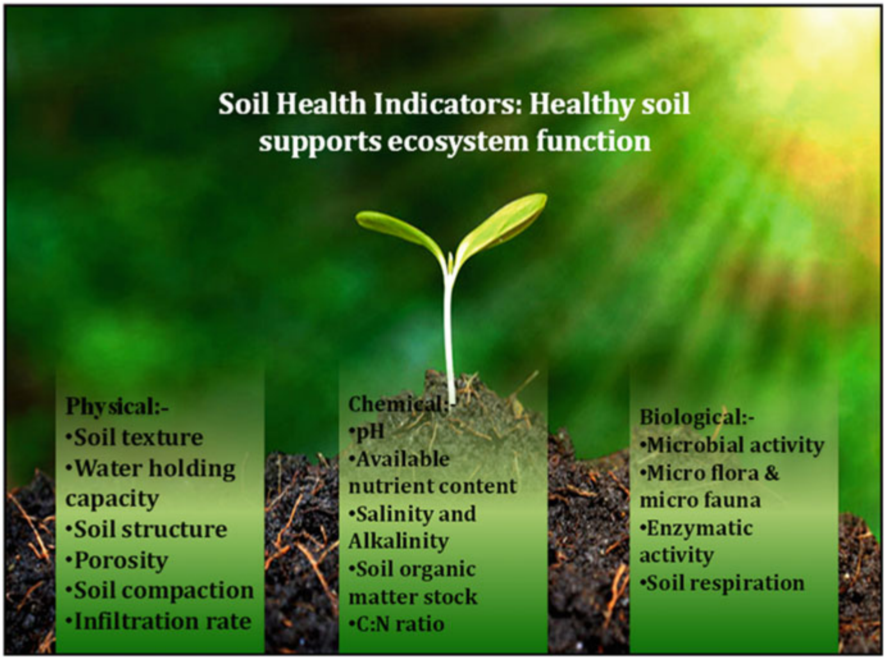

Fig. 10.3 Soil health indicators for improving fertility and productivity

including intensive agriculture have been evolved that produces more. Intensive agriculture refers to the farming practices where heavy machinery, fertilizer, plant protection chemicals, labor, and capital are being used to keep the pace of agricultural productivity in accordance with increasing population (Wu and Li 2013). However, intensive farming by using modern technologies has gradually become the biggest threat to the soil health. Application of higher doses of synthetic fertilizers and pesticides, excessive irrigation, focus on the cultivation of crops of greater remuneration, intensive tillage of soil, and performing all these using improved heavy-weight farm machinery for common practices in intensive agriculture. Although, it has enabled us to produce more food to feed the growing population, in long run it affects the soil health negatively. The noxious impacts of intensive agriculture on soil health can be direct as well as indirect through climate change as it eases climate change through the emission of Greenhouse Gases (GHGs) (Tollefson 2010). Among the total anthropogenic emission of GHGs, the activities involved in Agriculture, Forestry, and Other Land Use (AFOLU) exclusively contribute around CO_2 (13%), CH_4 (44%), and N_2O (82%) emissions in between the period of 2007 and 2016 (IPCC 2019). Intensive agriculture that maximizes global warming potential increases the soil temperature which hampers all the physical, chemical, and biological aspects of soil health.

10.3.1 Impact of Land-Use Change on Soil Health

Changes in land-use pattern for intensive agriculture resulting in degradation of soil quality and subsequent crop productivity (Crodovil et al. 2020). Soil and chemical runoff by water may negatively affect the adjacent area (Wu and Li 2013). The conversion of natural ecosystem to farming production system rapidly decreases the soil C stock due to heavy decomposition of surface vegetation and SOC mineralization. The loss of soil C is also mediated by land erosion, leaching, and the use of heavy machinery. Soil physical properties viz. bulk density, soil structure, and infiltration rate are negatively affected by continuous intensive tillage operation (Crodovil et al. 2020). The erosion hazards increase with intensive tilling of soils through which the fertile topsoil is removed thus makes the soil sick. Since organic carbon is the most important indicator of soil health (Tripathi et al. 2020), its depletion results the destruction of soil aggregate stability, bulk density, water infiltrations and storage and increase in crusting, compaction, and wind and water erosion, which are major constraints to crop production (Lal 2005). Soil is being lost faster than it can be replaced (Panagos et al. 2015), which affects the restoration of soil health in the natural way.

10.3.2 Impact of Heavy Fertilizer Use on Soil Health

Soil physical, chemical, and biological properties are significantly influenced by the Soil Organic Matter (SOM) considering the most crucial parameter of soil health indication (Tripathi et al. 2020). The use of chemical fertilizers in longer duration influences soil organic stock, pH, EC, soil moisture that makes the variation in nutrient availability to microbes change with long-term use fertilizers (Tripathi et al. 2020). Soil acidification, release of particle binding soil cations like calcium (Ca) and magnesium (Mg) are facilitated by the excessive use of synthetic N fertilizers.

Further, the continuous application of inorganic nitrogenous fertilizer in long run may deplete the number of base cations, facilitating the greater release of aluminium ion (Al^{3+}) from soil minerals, often cross the sustain limits that eliciting plant nutrient disorders (Tripathi et al. 2020). Severe soil acidification has been reported in China owing to injudicious synthetic fertilizer use that makes severe crop damage in a larger area (Guo et al. 2010). A huge amount of nitrous oxide is generated due to the soil acidification through rapid nitrification and denitrification. Venterea et al. (2004) reported a negative indirect effect of soil acidification on microbial population. Soil N, P, and C are the major sources of energy to soil microflora (Cruz et al. 2009; Liu et al. 2010; Yang et al. 2011; Lupwayi et al. 2012). However, the excess application negatively influences the living communities and disrupts their activity in soil; most particularly, they are very much sensitive to a high level of inorganic N fertilizer (Kibblewhite et al. 2008). Mondal et al. (2020b) established that a high level of N significantly reduced the rhizobium population in peanut while moderate level significantly improved their population throughout the whole growing periods.

A similar result also observed in case of total bacterial population and free-living fungi which would be slowed down the mineralization process and nutrient recycling (Velthof et al. 2012).

Increased leaching of nitrate and other cations (Ca, Mg) is observed with the application of excessive chemical fertilizers, accelerates the chance of eutrophication and quality deterioration of surface as well as ground water. Moreover, the leached nitrate accelerates the process of pyrite oxidation in subsoil, resulting in the release of nickel (Ni), arsenic (As), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), zinc (Zn), considered as the potential soil pollutants (Liu et al. 2010).

10.3.3 Impacts of Pesticides on Soil Health

The pesticide application in an optimum dose protects the crop from harmful disease, insects, and weeds infestation; however, recent repetitive application of high dose agrochemicals alters the equilibrium of soil ecology depend upon the persistence, intensity and mode of action (Margni et al. 2002; Mandal et al. 2020). Pesticides have a direct detrimental effect on metabolic function of soil living organisms that may alter the physiological and biochemical properties of macro and microflora (McLaughlin and Mineau 1995; Singh and walker 2006). The inhibitory effect on soil microorganisms ultimately affects on nutrient mobilization, biological N-fixation and organic matter decomposition (Sardar and Kole 2005); thus degrades the soil quality. It has been well reported that copper-based fungicides have roles in the minimization of soil earthworm population (Van Zwieten et al. 2004; Eijsackers et al. 2005).

10.3.4 Impact of Using Heavy Machinery on Soil Health

Intensive mechanization in farming activities is the major reason for creating soil compaction in the subsoil layer. It would be harmful to soil physical, chemical, and biological properties and the compaction make it difficult in well-crop establishment, root proliferation, water, and nutrient movement as it degrades the soil homogeneity in pore system (Horn et al. 2003; Servadio et al. 2005). The deterioration of soil pore restricts the hydraulic conductivity, infiltration rate, and facilitate greater runoff (Chamen et al. 2014; Soracco et al. 2015).

10.4 Strategies to Enhance Input Use Efficiency to Improve Soil Fertility and Productivity

The innate capacity of soil to provide nutrients in plant-available forms and its ability to produce economic yield are known as soil fertility and productivity, respectively. The present intensive system has undesirable effects on the soil environment, both structural and microbial (Bahadur et al. 2020). The degradation of soil health is responsible for gradual yield reduction even with the application of heavy inputs because of the reduction in soil fertility and productivity thus reducing the input use efficiency.

The improvement of resource use efficiency along with high productivity and environmental viability in limited land is an essential target in the situation of over increasing population, intense food demand, and global financial crisis. Several approaches have introduced for efficient management of resources available to improve the input use efficiency thus fostering the soil fertility and productivity.

10.4.1 Residues Management

Crop residues are considered as a renewable resource having significant contribution to conserve the nonrenewable crucial natural resources, i.e., soil and water and maintain the system sustainability. In-situ crop residue management reduces the chance of soil erosion with low-environmental pressure (Tewari and Pareek 2018). Crop residues are the primary source of organic matter (Jat et al. 2014) that also adds some amounts of essential nutrients to soil through nutrient recycling. Application of crop residues in soil enhance the soil organic matter content that improves the soil physical and chemical properties and provides a better growing condition to beneficial micro- and macro-organisms. Harvested crop residues may be used as organic mulches for forthcoming crops, raw material in industry and compost making, fuel in the household, and animal foods (Lal 2005). Scientifically, well managed and cost-effective residue management practices are needed to be developed for eco-friendly crop production (Jat et al. 2014).

10.4.1.1 In Situ Incorporation of Crop Residues

In situ crop residue incorporation has several advantages though it temporarily immobilizes the soil available N due to presence of high C:N ratio. Therefore, an extra dose of N fertilizer should be given at the time of residue retention (Yadvinder-Singh et al. 2005; Bijay-Singh et al. 2008a). There should be 10–20 days between residue incorporation and crop sowing for well-decomposition (Yadvinder-Singh et al. 2004).

10.4.1.2 Surface Retention of Crop Residues

To overcome the negative effect of intensive tillage on soil carbon pool and soil physical properties, conservation agriculture system has been introduced that emphasizes the surface retention of crop residues. Soil and water conservation, maintaining of soil favorable temperature, reducing weed infestation and surface evaporation, and the supply of soil organic matter by crop residue incorporation facilitate to better crop productivity (Mondal et al. 2018).

In rainfed agriculture, rainwater infiltration and storage in post rainy fallow lands is significantly improved by retaining crop residues on the soil by minimizing the physical impacts of raindrops on the surface soil. Covering soil with crop residue can help in checking soil loss due to erosion. Surface mulch moderates soil temperature and can reduce maximum soil temperature by as much as 10 °C at 5 cm depth during the summer months (Jat et al. 2014). Crop residue retention may often temporarily lock the N availability as a result of higher N immobilization, denitrification, and ammonia volatilization, particularly, at the early growth phase (Jat et al. 2014).

10.4.1.3 Crop Residues as Biochar

Utilizing the crop residues to produce certain substances like biochar that can be used as an amendment to improve soil fertility and productivity has been proved to be effective. Biochar is a carbon-rich substance manufactured through pyrolysis where waste materials are burned 300–600 °C in the fractional or total omission of oxygen. Biochar production and its application has been reported as an efficient eco-friendly way of waste biomass diversification to generate carbon pool in soil. Biochar application to soil reduces soil acidity, improves water holding capacity and cation exchange capacity and reduces the emission of GHGs (Singh et al. 2019).

10.4.1.4 Crop Residues for Composting

Composting from crop residues and dairy manure can be a management strategy of residues. The mixing of dung and crop residues keeps better moisture and more impartial nutrients for the microorganisms to carry out the composting mechanisms. Several methods have been developed to make compost using the crop residues. Compost can be applied to soil as organic manure that increases the soil organic matter, enhances the soil nutrient pool and enriches the soil microorganism biomass, important for soil health.

10.4.2 Precision Nutrient Management with Modern Concept

The growing and competitive demand for food, feed, fiber, and bioenergy crop products are seriously damaging the world’s soil resources (Johnston and Bruulsema 2014). Deterioration of soil reduces the quantity and availability of essential nutrients present in it and leads to a fall in productivity as plants badly need these nutrients to complete their life cycle. Application of chemical fertilizers is the most adopted practice to replenish this essential nutrient concentration in soil. However, the indiscriminate use of synthetic fertilizers has several negative impacts on soil health. This drives scientists to think of a regulated nutrient management strategy that integrates with agronomic best management practices to achieve crop management objectives (Fixen 2009).

The 4R nutrient stewardship is comprised of using the right type of fertilizer at right time with the right amount to the right place (Roberts 2007; Banerjee et al. 2019). These four “rights” are all necessary the sustainable management of plant nutrition.

10.4.2.1 Right Product

Choosing the right product in accordance with the soil pH, salinity, water holding capacity and other physic-chemical properties to make the holistic interaction between the applied fertilizer with soil properties is one of the crucial factors for better nutrient use efficiency (Roberts 2007).

10.4.2.2 Right Rate

Precise fertilization according to soil test-based nutrient demand or crop need with the help of modern techniques helps to improve nutrient use efficiency, lowering the chances of losses, and GHGs emissions (Banerjee et al. 2019).

10.4.2.3 Right Time

The synchronization of fertilizer application time with crop demand with the help leaf color chart, SPAD meter, or visual symptoms makes nutrient more efficient to crop growth. Split application, controlled release technologies, use of stabilizers, product choice, and sensor-based tools are important examples of best management practice the help in the timing of nutrient availability (Garai et al. 2020).

10.4.2.4 Right Place

Adoption of site-specific nutrient management rather than blanket application reduces the fertilizer requirement as the place from where the crop can mitigate their nutrient requirement efficiently is a very crucial factor. Right place along with conservation tillage, buffer strips, cover crops, and water management facility to maximum accessibility of plant nutrients (Fixen 2009).

Source, rate, time, and place are completely interconnected in nutrient management. With one of these wrong others cannot be right. For a certain situation, it is possible to have more than one correct combination, but with the change in one of these four rights, others may change as well. The 4Rs must work in synchrony with the cropping system and management practices to fully exploit its advantages with respect to the social, economic, and environmental aspects (Fig. 10.4).

10.4.2.5 Site-Specific Nutrient Management

The nutrients requirement by the plant to account for maximum economic return per unit of nutrient input varies with different locations, growing seasons, and years. The principle of site-specific nutrient management involves the feeding of crops when needs (Fig. 10.5), aims to the use of fertilizer optimally to fill the nutrient deficit of high-value crops (Ahmad and Mahdi 2018; Buresh and Witt 2007). This approach was first introduced in rice cultivation; however, it can be applied to any crop and it forms an important component of precision agriculture. Three steps are involved to determine the optimum amount of essential nutrients required for a crop as and when needed to fulfill maximum yield potential (Buresh 2007). It has been well reported that the SSNM approach significantly improves the farmers economic return from on-farm trials in tropical Asia since the last 20 years by around 100 USD ha^{-1} (Pampolino et al. 2007; Wang et al. 2007). Across the Asian countries, it has been well reported that the application of SSNM-based fertilizers effectively increases productivity, nutrient use efficiency, and economic return (Dobermann et al. 2002; Dobermann et al. 2004).

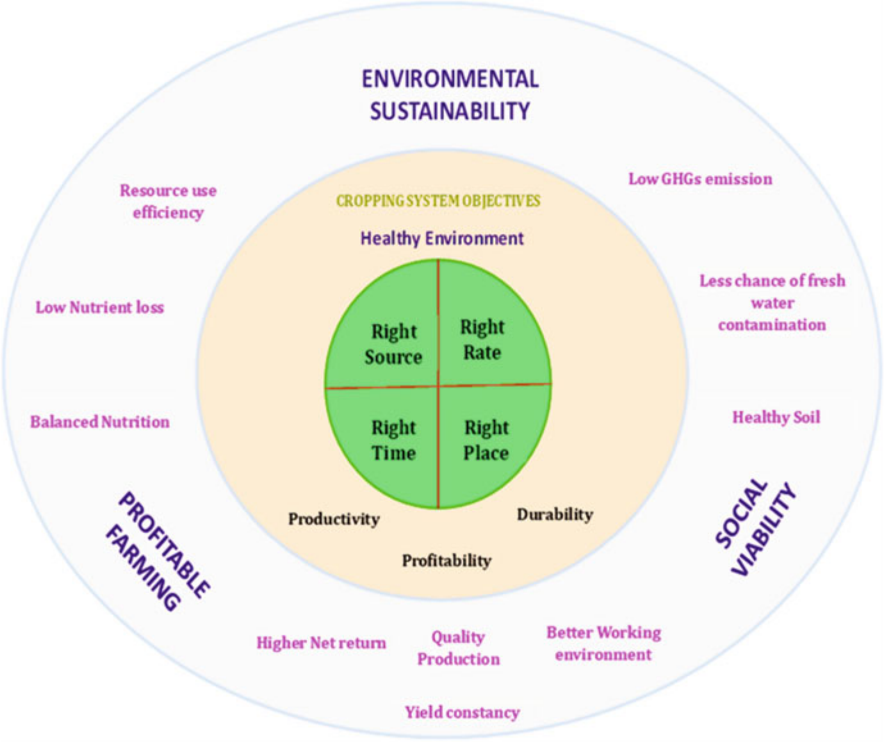

Fig. 10.4 4R principles in nutrient management (Roberts 2007)

10.4.3 Integrated Nutrient Management

The rational supply of plant nutrients from both organic and inorganic sources in an integrated approach to fulfill the aim of minimum chemical fertilizer use without compromising the crop yield is referred to as integrated nutrient management (Maiti et al. 2006). Integrated use of chemical fertilizers, organic manures, crop residues, and biofertilizers has become the need of the hour to improve the soil fertility and productivity that is degrading due to modern intensive agriculture. Integrated Nutrient Management (INM) or Integrated Plant Nutrient Supply System (IPNS) is an approach adapting the plant nutrition to specific farming systems and particular yield targets, the resource base, the available plant nutrient source and socioeconomic condition (Dudal and Roy 1995). Thus, it demands a holistic approach to nutrient management for agricultural production. All the sources of incoming nutrients including irrigation water and outgoing nutrients from a farm are to be monitored to make the INM programme successful (Prasad et al. 2014a, b). The basic principle of INM is consisted of the use of all available sources of nutrients precisely to account economic and environmental sustainability and the supply of quality food (Maiti et al. 2006; Grant et al. 2008). The available nutrient resources include the

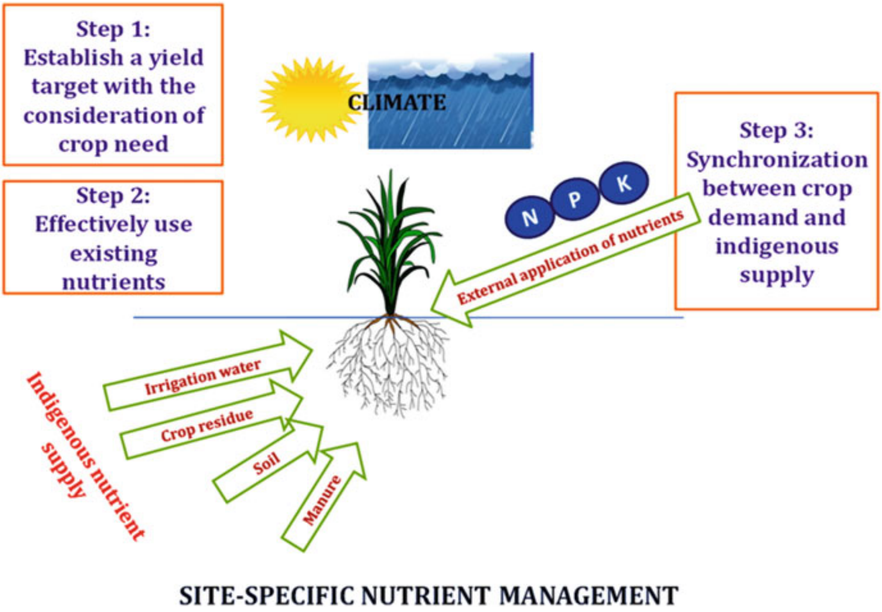

Fig. 10.5 Generic principles of site-specific nutrient management

nutrients from chemical fertilizers, organic manures, crop residues, soil and atmospheric deposition, and the nutrients released by soil biological activities (Esilaba et al. 2004; Zhang et al. 2012).

The more use of organic manures or other organic nutrient sources is the top most priority in INM as it has several benefits in soil health but obviously the productivity of crop should be taken into consideration. Organic sources not only help to release the nutrient during the entire period of crop growth but also improve the soil structure, water holding capacity, ion exchange, act as a buffering agent of soil pH and reservoir of entire range of plant nutrients. Application of organic matter helps to increase the soil microorganisms which lead to rapid decomposition and release of mineral nutrients in soil ecosystems (Wu and Ma 2015).

10.5 Frontier Agricultural Technologies for Improving Soil Health by Enhancing Input Use Efficiency

10.5.1 Climate-Smart Agriculture

The term climate-smart agriculture refers to comprehensive management strategies which recognize the threats of climate change that needs to be responded to take proper contingency measures against the particular occurrence for minimizing damage and ensure the preservation, restoration, and improvement of existing resources (Mondal et al. 2020a). The alteration of air temperature, wind movement, and erratic rainfall as a consequence of recent climatic abnormalities poses critical threats to ecosystem services and crop productivity with low-input use efficiency and loss of natural resources, mostly in the semi-arid and tropical region (World Bank 2006; Keesstra et al. 2016). Increasing soil temperature, changing rainfall pattern and CO_2 concentration adversely affects the nutrient mineralization, increase root exudates that alter buffer power, facilitates the rapid volatilization, leaching losses, nutrient diffusion, and soil moisture storage which may increase or decrease the nutrient movement in soil (Brouder and Volenec 2008). The topsoil erosion by heavy water and wind movement impairs the major nutrient reservoir and results in low-input efficient agriculture (Keesstra et al. 2016). Soil is considered as the key source of nutrients for the most living organism in the terrestrial ecosystem. Soil Organic Carbon (SOC) management as a climate-smart strategy is gaining importance worldwide due to its core relationship with numerous soil properties and relevant soil ecosystem functioning (Powlson et al. 2011). The atmospheric concentration can be altered even in small changes in large soil carbon stock. The twice quantity of carbon as the form of CO_2 presence in the atmosphere is equal to the soil carbon stock within 0–30 cm depth which may be an opportunity or threat to the global carbon cycle. The climate-resilient strategies in respect to soil and crop management are the major challenge to sequester more amount of carbon into the soil with sustaining higher productivity.

The improvement of soil carbon sequestration can be achieved in two major ways such as enhancing the photosynthetic transformation to soil organic matter and slowing the organic matter decomposition rate. As an example, the biochar application has been popularized by many scientists and policymakers for better C sequestration, soil health restoration, and nutrient mobilization (Kookana et al. 2011). Additionally, it has been well reported that the improvement of root architecture with a well-distributed and deep penetrating root system through modern breeding programmes resulted in higher nutrient uptake and nutrient use efficiency (Wu et al. 2018). Moreover, the second-generation sequencing and associated bioinformatics in investigating the soil microflora and their interaction with plant roots and soil nutrients could provide a deeper knowledge of functional microbial diversity, soil biological mechanisms and soil ecology for practical approaches (Saleh-Lakha et al. 2005; Powlson et al. 2011).

Scientists have identified different Soil And Crop Management Strategies (SCMS) regarding precise nutrient management strategies to optimal input use efficiency with special consideration of environmental sustainability. These strategies aim to improve soil health and crop productivity by optimizing the soil physical, chemical, and biological properties with the help of balanced nutrient supply, integrated nutrient management and ration use of fertilizers when crop are needed mostly (Esilaba et al. 2005). The SCMS strategies should include two key principles, i.e., soil test-based and crop need-based input supply and synchronization of input application time with crop growth. This SCMS concept not only results in higher yield with low-input cost but also it is considered as the eco-friendly farming strategy (Cui et al. 2014). Practically, without the use of synthetic fertilizers, the yield improvements would not have been possible to mitigate the food demand in over increasing population. However, a large part of the synthetic fertilizers is not utilized by the plants and causes a significant contribution to environmental pollution (Zhang et al. 2013). Hence, balanced nutrients supply with precision tools in SCMS practices would be the better option to fulfill the goal of climate-resilient concept without sacrificing the crop yield (Nhamo et al. 2014). As an example, improved SCMS practices resulted in a 39% higher wheat yield with a 21% reduction of GHGs emission as compared to the conventional farming system (Cui et al. 2014).

10.5.2 Organic Agriculture

Organic agriculture refers to a modern farming practice without the use of any type of synthetic fertilizers or pesticide and mostly relies on crop rotation, natural pest management, use of compost, manures, and legume residues along with modern tools and techniques. According to National Organic Programme (NOP) an organic producer should be concerned with soil physical, chemical, and biological health (NOP§205.203). Previously, scientists are established that on average organic system produced 8--25% low yield as compared to the conventional system, which varied with different types of crops (Ponisio et al. 2014; Reganold and Wachter 2016). But it has been well reported that the organic system is very much reliable in abnormal climatic variability (Lotter et al. 2003). Additionally, organic agriculture helps to improve soil physical properties viz. water retention capacity, porosity, aggregation than conventionally managed soil (Gomiero et al. 2011) which could be beneficial to maintain system stability against climate change (Reganold and Wachter 2016). Moreover, organically managed soil improves soil carbon stock and soil organic carbon (Tuomisto et al. 2012). Organic agriculture helps to retain more nutrients in soil by preventing leaching loss and GHGs emission (Tuomisto et al. 2012). Application of well-decomposed FYM improves the soil organic matter that enhances the cation exchange capacity and is considered as the storehouse of available N, P, S; also, the key source of energy for soil microflora (Phonglosa et al. 2015). Undoubtedly, the organic farming influence the soil available nutrients, C:N ration, N mineralization, microbial activity, and soil texture that positively influence the overall soil health and use efficiency of crucial inputs (Agehara and Warncke 2005).

10.5.3 Nanotechnology-Based Input Management

Nanotechnology-based farming practices are one of the modern technological implementations in agriculture that precisely controls the input use and monitoring its quality for sustainable development (Prasad et al. 2014a, b). The nanotechnology includes the application of biosensors, nanotubes, nanofiltration, and controlled delivery system (Sabir et al. 2014). The use of these technology aims to precise resource management, rational application of agrochemicals to plant and helps to maintain the soil fertility. The nanomaterials, such as nano fertilizers, nano pesticides have a significant influence on soil surface structure, charge, aggregation, and chemical composition (Ion et al. 2010). The nanotechnology has been successfully implemented in agricultural waste management, food processing, and risk management (Floros et al. 2010). The contamination of soil and freshwater can be monitored by the application of nanosensors in agriculture, such as biosensors, electrochemical sensors, optical sensors, and heavy metal detectors (Ion et al. 2010). Additionally, nanomaterials help in organic matter decomposition by microorganisms. Bio-remediation is a part of nanotechnology that eliminates heavy metals and toxic substances from cultivable land and freshwater (Dixit et al. 2015).

Nano-fertilizers contents nano zinc, silica, iron, titanium, gold nanorods, and several plant growth regulators (Prasad et al. 2017). Nano fertilizers help to alleviate the demand for several micronutrients as well as it supplies vitamins, seaweed extracts, and plant growth hormones. This nanotechnology-based input opens the possibility of higher biomass productivity along with better utilization of organic waste inefficient way (Prasad et al. 2017). Recently, the nano encapsulated pesticides are popularized due to its slow-release properties, higher permeability, stability, and specificity to the target. These encapsulated nano pesticides significantly improve the pest control efficiency toward the whole crop growing period (Bhattacharya et al. 2016). Moreover, nano pesticides contain a low dose of pesticides which reduce the human health hazards and are treated as eco-friendly materials (Nuruzzaman et al. 2016).

10.5.4 Bio-Stimulates-Based Crop Production

The uses of bio-stimulation in agronomic crop management are a promising technique for better productivity, quality enhancement, nutrient use efficiency, and help to mitigate the several abiotic stresses (Colla and Rouphale 2015). Plant biostimulants are heterogeneous in nature, contains a range of beneficial elements, micro and macronutrients, natural hormones, seaweed extracts, complex organic materials, antitranspirants, free amino acids, and N-containing substances (du Jardin 2012). The application of *Trichoderma harziamum* on leafy vegetables resulted in better nitrogen use efficiency and facilitated the native soil N uptake (De Pascale et al. 2017). Additionally, bacterial inoculants help to improve higher nutrient availability. Among the nonmicrobial bio-stimulants, seaweed extracts are gaining considerable attention worldwide. It facilitates to improve the antioxidant properties, soil C stock and makes more nutrient availability toward plants (Kasim et al. 2016). Moreover, it lowers the fertilizer requirements; increases crop productivity, quality and postharvest shelf life (Kulkarni et al. 2019). Foliar application of bio-stimulants may be considered as additional irrigation to plant. Interestingly, bio-stimulant production does not entail any inputs from fossil fuels that lower the C footprint (Garai et al. 2019).

10.5.5 Conservation Agriculture

The term conservation agriculture is defined as a comprehensive farming system concept which includes maximum soil cover, low soil disturbance, and crop diversification to achieve indispensable quality in the agricultural system for livelihood security and maintain sustainability. Modern energy-intensive agriculture encourages frequent tillage, heavy machinery movement, irrational input use and clean cultivation which has been accused of soil erosion, natural's resource degradation, air and water pollution, and low use efficiency of farming inputs. The conservation agriculture relies on improving tillage practices viz. minimum tillage, zero tillage, stubble mulch tillage; crop diversification viz. horizontal diversification, vertical diversification, diversification through intercropping, mixed cropping, and crop rotation; permanent soil covering viz. stubble mulch, straw mulch, and polythene mulching (Garai et al. 2020). Such strategy facilitates the farming resources recycling, better water availability, low infiltration, promotes carbon sequestration and eliminates soil erosion, and improves the soil biological activities (Gonzalez-Sanchez et al. 2015). Additionally, Broudera and Gomez-Macpherson (2008) reported that conservation agriculture increases 33% yield in cereals crop along with ecological sustainability. Moreover, zero tillage resulted in higher monetary return over conventional tillage in the predominant rice–wheat system (Malik et al. 2002). It has been reported that land shaping techniques such as raised bed planting and laser land leveller saved 13–33% irrigation water and 75% of fossil fuel consumption (Humphreys et al. 2010). Crop residue incorporation resulted between 13% and 8% yield enhancement along with 13% and 6% greater energy use efficiency in rice and wheat, respectively, as compared to clean cultivation (PDFSR 2011; Mondal et al. 2020c).

10.5.6 Sustainable Land Management

Sustainable Land Management (SLM) is defined as the appropriate land-use system that enables the land user to maximize the resources utilization along with an economic return and social benefits without hampering the ecological balance. The land is considered as an important nonrenewable resource for the people who sustain their livelihood with agriculture. Disturbing this resource significantly hampers its existing biodiversity and ultimately affects crop productivity, hampers economic viability in the forthcoming future (FAO 2018a, b). The SLM approach aims to provide better land utilization under limiting resources, minimizing land degradation, rehabilitating degraded land, and optimize the resource utilization for the present as well as future generations (World Bank 2006). Good practices of SLM include stubble incorporation, cover crops, amendments of organic matters, integrated application of organic and inorganic nutrient sources, selection of site-specific cropping systems, site-specific land management, such as bed planting, ridge furrow, contour planting to achieve the land degradation neutrality. SLM significantly contributes in building up soil C (Lal 2013), mitigate yield gap

(Bruinsma 2009), increase the water and fertilizer use efficiency (Cowie et al. 2018) and reduce large-scale land degradation (Liniger et al. 2011).

10.5.7 Vertical/Sky Farming

Vertical farming is the most innovative and useful farming strategy in a recent era when huge population pressure, rapid urbanization and industrialization retard the cultivable land diversification (Despommiere 2013) while emerging world's population will demand 70% more food production in near 2050 (UN 2017). In this context, the logic of vertical farming, i.e., produces more food on less land to address the problem of farmland shortage is growing to be popularized (Thomar et al. 2015). In vertical farming, the crops are cultivated in aeroponics or hydroponics with the help of soluble mineral nutrients under indoor controlled environments. It helps to avoid crop damage due to climatic abnormalities or any disease pest infestation (Meinhold 2013). It also facilitates higher land productivity as the plants can be raised in multiple layers. It enables the chances of residues recycling, reduces the contamination of agrochemicals to the environments and minimizes the heavy fossil fuel consumption (Germer et al. 2011). The nutrients feeding through foliar spray or root dipping improves the use of efficiency and eliminates the chances of losses. Considering the huge advantage in vertical farming rather than the initial cost investment, scientists, and policymakers believe that it would be one of the best options for next-generation farming activities.

10.6 Constraints to Improve Soil Health

The intensive agricultural practices such as frequent tillage, use of heavy agrochemicals, clean cultivation along with recent climatic hazard deteriorate soil health significantly (Sivaramanan and Kotagama 2019). However, the constraints that deteriorate soil health are varied enormously with different farming system approach, agro-climatic condition and topographic situation. Farming interventions viz., powered tillage, dependency on inorganic sources of nutrients and pesticides affect the soil biological communities, their habitat, and function to varying extents (Kibblewhite et al. 2008). The following faulty agricultural practices make it difficult to improve soil health:

10.6.1 Clean Cultivation

Frequent cultivation with the clearing of surface vegetation to a great extent extremely affects on the soil organic matter content, lowering the cation exchange capacity and soil nutrients retention ability which would otherwise be leached to groundwater (Kibblewhite et al. 2008). Additionally, the naked surface leads to severe soil erosion along with the removal of root zone soil nutrient content.

Long-term surface erosion ultimately turns the cultivable land into degraded land (Kibblewhite et al. 2008).

10.6.2 Frequent Mechanical Tillage

Frequent mechanical tillage for intensive agriculture destroys the soil spatial integrity more precisely at meso-and macro-faunal scales. Moreover, mechanical tillage creates subsurface hardpan, degrades the soil structure, facilitates the soil erosion and it is well established that maximum number of earthworms are killed during this mechanical tillage (Landers et al. 2001). This process enhances soil carbon loss and reduces the levels of O, N, P, K, Ca, and Mg with increased tillage frequency (Adekiya et al. 2016).

10.6.3 Quality of Irrigation Water

Low-quality irrigation water which contains a higher level of dissolved mineral salts destroys the soil structure due to the presence of too much Na^+ ion; thus, it breaks down the infiltration tube and reduces the infiltration rate, thereby irrigation water use efficiency is decreased, increased runoff and soil water erosion (Mon et al. 2007). The presence of a little amount of salt can result in a chemically compacted soil (McKenzie 2010). Prolong application of saline or sodic water in irrigation purposes causes permanent soil sodification and alkalization (Mon et al. 2007).

10.6.4 Excessive Fertilization

Use of inorganic fertilizers improves the crop growth and yield within a short period of time, however extensive use of chemical fertilizers for longer duration makes soil more acidic and reduces the soil aggregation which leads to erosion (Ozlu and Kumar 2018). Excessive use of fertilizer prone to heavy contamination with groundwater as it is heavy water-soluble in nature and therefore absorb by ground more rapidly than plants. The reaction of chemicals with clay soil creates a hardpan that restricts the root penetration into soil, air, and water movement (Sarfaraz 2019). Chemical fertilizers also jeopardize the health of soil beneficial microorganisms, such as N-fixing bacteria (Sarfaraz 2019). An Arbuscular mycorrhizal fungus (AMF) is sharply decreased with the intensive use of N and P fertilizer (Ryan et al. 2000).

10.6.5 Injudicious Use of Chemical Pesticide

The application of pesticide in a higher dose may affect the soil microbial activities and such changes may deteriorate soil fertility (Lo 2010). As an example, the application of glyphosate reduces the root colonization of AMF which has significant contribution in water access and nutrient solubilization for plants; additionally, it helps in drought tolerance and pathogen resistance (Druille et al. 2013). Actually, the persistence of herbicide in soil is the major threat to soil biological ecosystem (Thiour-Mauprivez et al. 2019). Low microbial population 5 days after herbicide application was recorded by Silambarasan et al. (2017). The leaching or runoff of excess herbicides from soil results in contamination with groundwater and fresh surface water might be hazardous for the living organism (Noshadi and Homaee 2018).

10.7 Conclusions and Future Thrust

Global food production to feed the future population without hampering system sustainability is the greatest challenge in agriculture. There is no easy way to increase productivity in the limited land situation along with optimization of input use and maintaining environmental quality. Additionally, resource constrain, temperature rising, higher GHGs emission, and environmental pollution have made agroecosystem more vulnerable than ever before that creates extreme pressure on farming communities in developing and underdeveloped countries. Fortunately, scientists have developed several mitigation options through agronomic intervention and technological intervention to alleviate the predicted threat in future to some extent. This multifaceted intervention involved climate-resilient agriculture, soil and crop management practices, precise use of agrochemicals and more efficient utilization of farming inputs to minimize the soil health hazard, improve crop productivity along with special emphasis to environmental protection. Organic agriculture, conservation practices and need-based location-specific crop nutrient supply improve the physical, chemical, and biological soil properties. Moreover, the technological intervention in farming practices, such as precision agriculture, remote sensing, nanotechnology, and crop modeling, are also gaining considerable attention to predict the future agricultural threats that help to take the strategic solution from the beginning. Sustainability in agriculture with special emphasis on input use efficiency holds promise to future generation to produce more food with minimum resource use in an eco-friendly way and it can be successfully implemented if all the nations stand together and thus seek our common future.

Furthermore, additional multidisciplinary explorations are needed to itemize more precise application of crucial farming inputs from more organic sources instead of chemical sources. Cultivation of major food crops with legumes should give more emphasis to ameliorate soil health. Government and policymakers must allocate more funds for implementation of modern precision tools in farming activities thus farmers can easily access the right time, dose, and methods of input supply. Most importantly, global cooperation is needed to fulfill the goal of input efficient agriculture and to ensure rapid progress in future.

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Efficient Use of Nitrogen Fertilizers: A Basic Necessity for Food and Environmental Security

11

Bijay-Singh, Ali M. Ali, and Varinderpal-Singh

Abstract

Use of Fertilizer Nitrogen (N) to increase food production constituted one of the major factors in supporting population growth in the twentieth century. The trend continues in the twenty-first century, particularly in the developing countries of the world. Because a part of the N applied as fertilizer is prone to be lost from the soil–plant system to the environment and degrade its quality, increasing fertilizer N Use Efficiency (NUE) in agricultural farms can lead to achieving both food and environmental security. However, it is a challenging task because NUE is determined by a host of factors including nature of the crops grown, soil quality, and management of fertilizer N and other farm operations. In developing countries like India, China, and Egypt, NUE is rapidly falling since the Green Revolution era because consistently increasing fertilizer N consumption is accompanied by declining crop yield response to applied N. While in countries like the USA, crop yields continued to increase moderately even with a trend in the reduced increase in fertilizer N inputs, in most of the western European countries crop yields continued to improve without further increase or even decrease in fertilizer N consumption since the 1980s. These trends in crop yield and fertilizer N consumption in several developed countries have resulted in a regular increase in NUE for more than the last four decades. In line with the observed trends in NUE in countries like India and China, high N surpluses in agricultural soils are posing a threat to the environment. New knowledge-based N management strategies to improve NUE are becoming available, but significant new investments and partnerships between farmers, scientists, economists, citizens, and industries

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will be needed to improve NUE in current and future agricultural systems by the widespread adoption of both the existing and emerging technologies.

Keywords

Nitrogen use efficiency · Nitrogen input · Nitrogen output · Nitrogen surplus · Nitrogen balance · Partial factor productivity · Agronomic efficiency · Recovery efficiency · Soil nitrogen

Abbreviations

AE	Agronomic efficiency
DCD	Dicyandiamide
DMPP	3,4-Dimethylpyrazole phosphate
F	Fertilizer nitrogen level
N	Nitrogen
NBPT	N-(n-butyl) thiophosphorictriamide
NUE	Nitrogen use efficiency
PE	Physiological efficiency
PFP	Partial factor productivity
RE	Recovery efficiency
Rfc	Ratio of fertilizer to crop price
U	Total plant nitrogen uptake with nitrogen fertilizer
U_0	Total plant nitrogen uptake without nitrogen fertilizer
Y	Crop yield with fertilizer nitrogen
Y_0	Crop yield without fertilizer nitrogen
Y_F	Yield increase due to fertilizer nitrogen
Ymax	Yield at saturating fertilizer nitrogen levels

11.1 Introduction

Due to the increasing global population as well as improving standards of living, demand for food by 2050 should be 1.5–2 times as much as it is today. As per FAO's projection, there will be 60% higher agricultural production in 2050 than that recorded in 2005 to 2007 (Alexandratos and Bruinsma 2012). To achieve such food production levels without adding more farmed land, nitrogen (N) fertilizers produced by Haber–Bosch process are likely to continue playing a crucial role. According to Erisman et al. (2008), about 50% of the world population in 2008 was alive due to increased crop production achieved by applying fertilizer N. As depicted in Fig. 11.1, it is true even today and growth of the world population is more or less parallel to the rate of increase of fertilizer N consumption. Although production of enough fertilizer N and its reliable supply has allowed farmers to greatly increase

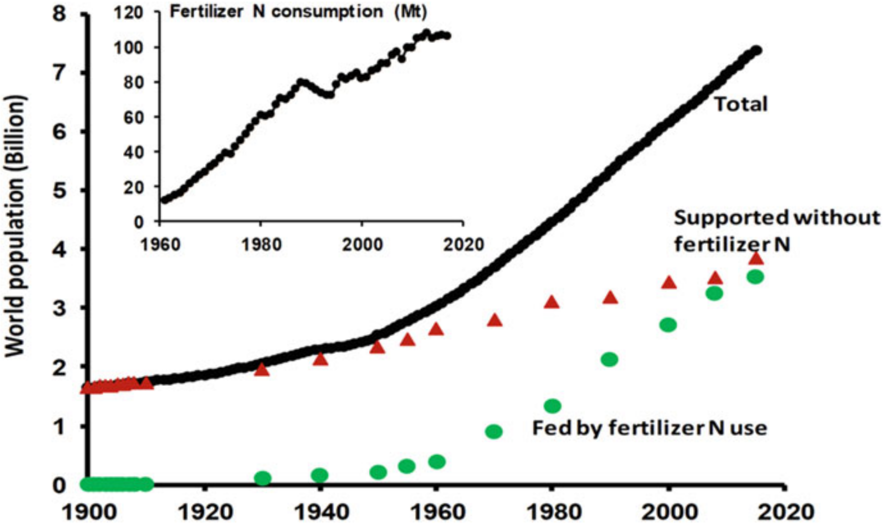

Fig. 11.1 Estimates of the share of the global population, which could be supported with and without the application of nitrogen fertilizers for food production on farms. Best estimates project that just over half of the global population could be sustained without applying nitrogen fertilizers on farms. Source: Erisman et al. (2008), Smil (2001), Stewart et al. (2005), IFADATA (2020)

crop production resulting in increased economic development as well as sparing forests from conversion to agricultural land (Foley et al. 2011), nearly one billion people all over the world still remain undernourished (Alexandratos and Bruinsma 2012; Kumar et al. 2018). It suggests that further improvement in fertilizer N management is needed to increase crop production per unit of applied fertilizer N.

Global fertilizer N consumption is increasing linearly (Fig. 11.1), but there exists wide variation in the extent of fertilizer N use in different countries of the world and in different regions within a country both in terms of total N consumption as well as consumption of N per ha of cropland. For example, until 1989 developed countries in the world consumed more fertilizer N than the developing countries, but later on, the consumption decreased in the developed countries but it is still increasing in developing countries (Bijay Singh and Ali 2020). Possibly, farmers in developed countries adopted improved fertilizer N management practices, which helped in producing high yield levels with less fertilizer N. Of the 107.7 Mt. fertilizer N consumed globally in 2017, 38.4% was used by farmers in China and India, the two developing countries where about 36% of the world population lives; North America and Western and Central Europe used only 25.4% of the fertilizer N consumed globally (http://ifadata.fertilizer.org/ucSearch.aspx, Accessed 8 August 2020). As fertilizer N is heavily subsidized in most of the developing countries, farmers often apply large N doses to avoid the risk of low crop yields but it leads to reduced N Use Efficiency (NUE). In Table 11.1 are listed data pertaining to fertilizer N use per unit area of arable land in different regions of the world in 2003 and 2018. In terms of agricultural intensification based on farm mechanization and the use of

Table 11.1 Fertilizer nitrogen use per ha of crop land in different regions of the world during 2003 to 2018

	Fertilizer N use (kg ha^{-1})			
Region	In 2003	In 2018	Absolute change	Relative change (%)
Middle Africa	0.89	2.44	+1.56	+176
Northern Africa	33.26	38.81	+5.56	+17
North America	61.65	72.32	+10.67	+17
Western Europe	136.27	118.52	−17.74	−13
Southern Asia	65.13	97.34	+32.21	+49
Eastern Asia	183.96	198.82	+14.86	+8
World	57.84	69.43	+11.59	+20

Fertilizer N use in kg ha^{-1} was calculated by dividing the fertilizer N consumption with area underarable land and permanent crops
Data source: FAOSTAT (2020)

fertilizers and chemicals, there exist large disproportions between different countries of the world (Mueller et al. 2012; Bouwman et al. 2013; Niedertscheider et al. 2016). In countries like China, Egypt, or in some parts of Europe, the application of heavy fertilizer N doses is resulting in a large amount of surplus N in the soil–plant system. But on the other hand, soils in many African countries are getting depleted of their N reserves due to the application of fertilizer N than less than the removal by crops (Sutton et al. 2013; Lassaletta et al. 2014; Kumar et al. 2020). Fertilizer N use per ha almost did not pick up in Middle Africa but it increased substantially in South Asia. In Western Europe and eastern Asia, fertilizer N use per ha was already very high in 2003 so that during 2003 and 2018, there was a relative increase of only 8% in Eastern Asia while a decrease of 13% was recorded in Western Europe. In 2018, China, Egypt, and India were applying 186, 276, and 97 kg N ha^{-1}. Thus, there are regions in the world where fertilizer N application rates are not even enough to achieve the full production potential of crops and in several countries, fertilizer N is being applied in farms at levels that may well exceed the N needs of crops.

While in natural ecosystems N present in the soil meets the N requirement of the growing plants, in the modern agro-ecosystems fertilizer has to be applied to supplement soil N to achieve N uptake levels of the crops needed to produce optimum yields. But fertilizers besides supplying N can also disturb microbial and other functions of the soil and different ecosystem services it performs. When fertilizer N is not efficiently utilized by crops due to excessive application levels and/or mismanagement, a portion of applied N may leave the soil–plant system and adversely impact the environment including groundwater contamination with nitrate-N, eutrophication of surface water bodies, and production of nitrous oxide—a greenhouse gas (Galloway et al. 2003, 2008; Reay et al. 2012). When applied in doses more than the requirement of the crops, fertilizer N leads to increased residual inorganic N in the soil, which accelerates the loss of soil organic matter through its mineralization leading to the deterioration of soil health (Bijay Singh 2018). Thus, too little N in the soil leads to reduced crop productivity, soil degradation, reduced protein intake by humans, and overall food insecurity but an excessive supply of N can result in environmental insecurity along with concomitant threats to human health, ecosystem health, and economic prosperity. Under these circumstances, the best solution is to apply only enough fertilizer N that the crop does not suffer due to N deficiency but ensure that a large portion of the applied N is used by crop plants and minimal amount escapes from the farms. It can be achieved by ensuring high fertilizer NUE, which represents the percentage of applied fertilizer N recovered in the farm produce, and it is the most effective means for achieving food security through increased crop productivity on the one hand and environmental security through reduced losses of N from the soil–plant system on the other (Cassman et al. 2003; Davidson et al. 2015). According to Zhang et al. (2015a), improvements in NUE in crop production, although conditional on the farm-scale adoption of innovative technologies and improved fertilizer management practices as well as on socio-economic factors, are critical for achieving food and environmental security, and resist climate change. In the fourth session of the United Nations Environment Assembly (UNEA 4) held in March 2019, a resolution passed on sustainable N management calls upon improving NUE for achieving the Sustainable Development Goals (UNEA 2019). This chapter is an attempt to discuss NUE in terms of the fertilizer N transformations in the soil and ways and means based on advances in technological capacity for knowledge-based N management in agriculture to improve NUE for achieving food security with minimal environmental degradation.

11.2 The Fate of Fertilizer Nitrogen in the Soil-Plant System

In all the soils, whether in unmanaged natural ecosystems to which no fertilizer N is applied or in agricultural ecosystems to which N is applied through fertilizers, N retention in organic combinations is a characteristic feature. As shown in Fig. 11.2, mineral N released through mineralization-immobilization turnover from the huge soil N pool remains available in a mineral N pool from which N is used by plant roots or it can be lost via leaching and/or in gaseous forms. At any time, soil N pool is huge in comparison to mineral N pool which continuously gets replenished at rates defined by moisture and temperature conditions (Fig. 11.2). In natural ecosystems, N released from the soil and its removal by roots of plant communities are synchronized both temporally and spatially to a very large extent so that losses of N from the soil–plant system are minimal. It represents a case of a relatively tight N cycle (Christensen 2004; Kumar et al. 2021). When fertilizer N is applied to agricultural soils, only a portion of it directly contributes to the mineral N pool, from where roots of crop plants absorb N or it can be lost to the environment via different mechanisms. The remaining portion of the fertilizer N becomes a part of the large pool of organically bound N in the soil. Chien et al. (2009) collected data from 800 experiments and found that recovery of applied N by cereal crops was only 51% and that fertilizer N recoveries were even lower when fertilizer N was applied at high rates.

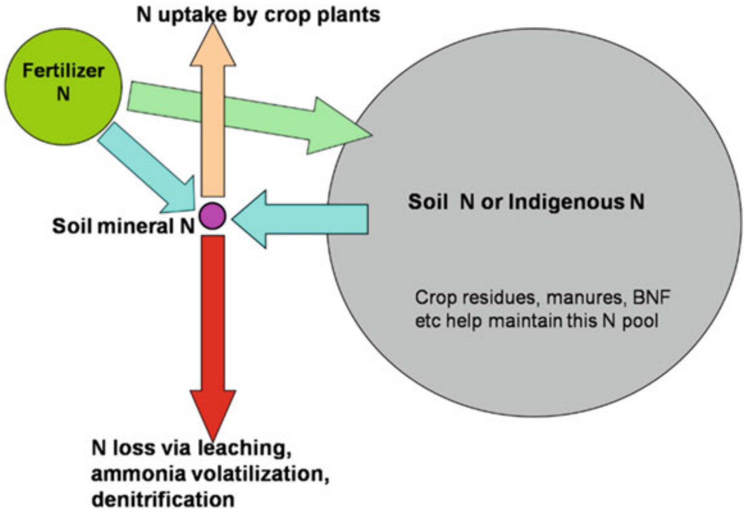

Fig. 11.2 Schematic diagram of the fate of fertilizer N applied to agricultural soils

Table 11.2 Typical range of grain yield and total amount of N removed by wheat, maize and rice

Crop	Yield per crop (t ha^{-1})[a]	Annual N removed (kg N ha^{-1})
Wheat (*Triticum aestivum*)	2–8	40–160
Maize (*Zea mays*)	3–8	45–120
Rice (*Oryza sativa*)	3–8	70-190[b]

[a] Lægreid et al. (1999)
[b] For two crops of rice grown in a year

In contrast to the natural ecosystems, N cycling in the agro-ecosystems is relatively open with other ecosystems. The yield and amount of N typically harvested in agricultural systems based on the three most important cereal crops are shown in Table 11.2. To maintain the productivity of these systems, N has to be applied as fertilizers, manures, or N_2-fixation to compensate for the removal of N to the extent of 300 kg N ha^{-1} each year in the form of harvested crops (Cassman et al. 2002). When enough fertilizer N is not applied in agro-ecosystems, soil N gets depleted. According to broad estimates, 20 to 80% of the N taken up by crop plants originates from soil N (Broadbent 1984). Although the rest of the N in crop plants is supplied by fertilizers, several studies prove that annual fertilizer N inputs are still more than the quantity of N removed in crop harvest by 40% to more than 100%, leading to loss of N to the environment (Galloway and Cowling 2002).

Despite some limitations (Stark 2000), ^{15}N-labeled fertilizers when applied to agricultural crops permit quantification of applied N in crop and different soil N pools. Based on data from 93 published studies (572 data points) from all over the world that used ^{15}N-labeled fertilizer, Ladha et al. (2005) revealed that the overall recovery of fertilizer N in the above-ground portions of maize, rice, and wheat was

Table 11.3 Percentage of soil N and fertilizer N in total N uptake by above-ground portions of different crops grown in different countries as determined by applying ^{15}N labeled fertilizers

Crop	Countries	Fertilizer N applied (kg N ha^{-1})	Total N uptake by the crop (kg N ha^{-1})	N in the crop derived from fertilizer (%)	N in the crop derived from soil (%)
Wheat	Bangladesh, Chile, Egypt, Morocco	42–160	60–161	16–43	57–84
Maize	Chile, Malaysia, Sri Lanka, Vietnam	60–300	53–178	18–58	42–92
Rice	China	60	292	7	93
Sugarcane	Brazil	63	251	16	84
Sunflower	Morocco	35	129	7	93
Bean	Morocco	85	225	7	93
Mean			147 ± 6	21 ± 1	79 ± 1

Modified from Dourado-Neto et al. (2010)

44%. A limited number of studies also exists in which recovery of ^{15}N-labeled fertilizer N has been studied even after the first crop (Hart et al. 1993; IAEA 2003; Kumar and Goh 2002). Mean recoveries of applied fertilizer N in first to fifth subsequent crops in different cropping systems were found to be 3.3%, 1.3%, 1.0%, 0.4%, and 0.5%, respectively so that in the six continuous crops only about 50% of the applied fertilizer N was recovered by crop plants. Thus as shown in Fig. 11.2, most of the remaining 50% of the remaining N applied through fertilizer was converted into organic N in the large soil N pool. Depending upon the closeness of the fertilizer N dose to the optimum for a crop, a part of the applied N should be directly susceptible to losses from the soil–plant system to the environment. In ^{15}N-recovery experiments conducted by Dourado-Neto et al. (2010) in diverse tropical locations, the average total contribution of ^{15}N-labeled fertilizer N by different crops was found to be 21% (7–58%) of the average crop N uptake of 147 ± 6 kg N ha^{-1} (Table 11.3). Thus, on an average 79% N in the above-ground crop plants was contributed by soil N. Based on data generated from 217 field studies in temperate grain agro-ecosystems in which ^{15}N-labeled fertilizer was applied, Gardner and Drinkwater (2009) also revealed that even with the application of high fertilizer N application rates, about 60% plant N came from soil N. That contribution of N released through mineralization of soil N is very crucial in supplying N to the growing plant even when the optimum amount of fertilizer N is applied, is an important finding and it has implications for both N nutrition of crop plants and environmental degradation. Sebilo et al. (2013) made a one-time application of ^{15}N-labeled fertilizer N at 120 kg N ha^{-1} to wheat and 150 kg N ha^{-1} to sugar beet grown under rotating cultivation in two intact lysimeters. Later on for three decades annual N fertilization rate for both crops was 120 kg N ha^{-1}. All the crops grown for three decades used only 61–65% of the applied fertilizer N. Substantial portion of the applied fertilizer N rapidly became a part of the soil N pool. While

32 to 37% of the applied N was incorporated in the soil organic matter after 3 years, 12–15% of the fertilizer N was still recovered in the soil N pool even after 28 years.

11.3 Measuring Fertilizer Nitrogen Use Efficiency

Nitrogen use efficiency is commonly used as a generic term and can be defined based on different components as in the specific indices listed in Table 11.4. Different indices of fertilizer NUE are essentially the ratios between crop output (economic yield or N uptake) and N inputs in the form of fertilizer (Crop Science Society of America 1992). Keeping in view that NUE is governed by efficiency in uptake and utilization of N for production of grains (Moll et al. 1982), indices of NUE have been classified as agronomic efficiency (AE), physiological efficiency (PE), recovery efficiency (RE) and partial factor productivity of applied N (PFP). Some other indices have also been used, but they have no additional advantage in studying the fate of fertilizer N in improving the N nutrition of crops (Huggins and Pan 1993). Recovery efficiency measured using ^{15}N-labeled fertilizer N can provide detailed information on the fate of applied N in terms of utilization by crop plants, losses from the soil–plant system, immobilization, and mineralization of soil N.

In field studies, the three NUE measures—RE, PE, and AE are computed from the increase in crop yield and/or N uptake by applying fertilizer N. These NUE measures are commonly referred to as computed by following the “difference method”. When using ^{15}N-labeled fertilizers, uptake of fertilizer N by the crop also provides a measure of NUE. Time scale for estimating RE, PE, and AE is usually one cropping season and these are based on a spatial scale mostly of a field or plot. When comparing different cropping practices in which crop yield in plots receiving no fertilizer N (Y_0) differs greatly due to following these practices, AE and RE are not appropriate indices of NUE (Dobermann 2007). In such scenarios, partial factor productivity (PFP) of fertilizer N (the ratio of grain yield and amount of fertilizer N applied) serves as the proper index of NUE as it allows making comparisons across agronomic practices since measurements of grain yield or N uptake in no-N control plots are not required in calculating PFP. In Table 11.4 are described the calculations, interpretation, and optimum range of different fertilizer NUE indices in cereal crops.

11.4 Fertilizer Nitrogen Use Efficiency and Crop Production

As discussed in the previous sections, all N applied as fertilizer is not available to the crop and the N applied through fertilizer constitutes only one of the several N sources in the soil. Therefore, NUE expressed as PFP provides a measure of the total economic output as a result of N utilization from all sources of N including fertilizer. Farmers also prefer to measure NUE as PFP as it provides a measure of the return from the application of fertilizer N, regardless of the indigenous soil supply. As yield (Y) recorded by applying fertilizer N at a given rate (F) represents the sum

Table 11.4 Definition, calculation, range and interpretation of different fertilizer nitrogen (N) use efficiency indices in cereals

Nitrogen use efficiency index	Formula[a]	Explanation	Range
RE, Apparent recovery efficiency of fertilizer N (kg increase in N uptake per kg fertilizer N). It can also be expressed as percentage of applied fertilizer N	RE = $(U - U_0)/F$ or RE = $(U- U_0)/F \times 100$	• Defined by congruence between plant N demand and N supplied by fertilizer. • Affected by the amount, time of application, placement, and form of fertilizer N, and factors controlling the size of the crop nutrient sink	0.30–0.50 kg/kg In well-managed crops, at low fertilizer N levels, or at low soil N supply, RE can be 0.50–0.80 kg/kg
PE, Physiological efficiency of fertilizer N (kg yield increase per kg increase in N uptake from fertilizer)	PE = $(Y - Y_0)/(U- U_0)$	• Capability of a plant to translate N utilized from fertilizer into grain yield. It depends on genotype, environment and management. • Low PE suggests sub-optimal growth due to N deficiency, drought stress, heat stress, mineral toxicities and pests	40–60 kg/kg In well-managed crops, at low fertilizer N levels, or at low soil N supply, PE can be >50 kg/kg
AE, Agronomic efficiency of fertilizer N (kg yield increase per kg fertilizer N)	AE = $(Y - Y_0)/F$ or AE = RE × PE	• As AE is the product of RE and PE, it depends on management practices that affect RE and PE	10–30 kg/kg In well-managed crops, at low fertilizer N levels, or at low soil N supply, AE can be >25 kg/kg
PFP, Partial factor productivity of applied N (kg harvest product per kg N applied)	PFP = Y/F	• It represents combined use efficiency of indigenous and applied N • Both high indigenous soil N supply and high AE determine PFP	40–80 kg/kg In well-managed crops, at low fertilizer N levels, or at low soil N supply, PFP can be >60 kg/kg

Modified from: Dobermann (2007)

[a] Symbols used in equations: F: fertilizer N applied (kg N ha^{-1}), Y: yield of the crop with application of fertilizer N (kg ha^{-1}), Y0: yield of the crop (kg ha^{-1}) without fertilizer N, U: total N uptake by above-ground crop biomass at maturity (kg N ha−1) with application of fertilizer N, U0: total N uptake by above-ground crop biomass at maturity (kg ha^{-1}) without fertilizer N

of the yield without fertilizer N (Y_0) and the yield increase because of fertilizer (Y_F), the PFP can be expressed as:

$$\mathrm{PFP} = \mathrm{Y/F} = (\mathrm{Y_0} + \mathrm{Y_F})/\mathrm{F} = \mathrm{Y_0/F} + \mathrm{Y_F/F} \tag{11.1}$$

As Y_F/F is the ratio of net increase in grain yield due to application of fertilizer N and the amount of fertilizer N applied, it is equivalent to AE, which is the product of recovery efficiency (RE) and physiological efficiency (PE) (Table 11.4), PFP can be written as:

$$\mathrm{PFP} = \mathrm{Y_0/F} + \mathrm{AE} = \mathrm{Y_0/F} + \mathrm{RE} \times \mathrm{PE} \tag{11.2}$$

Thus, PFP represents an efficiency index, which is based on the yield of the crop due to N derived from the soil, RE, and PE. The term "Y_0/F" in the above equation suggests that PFP in farmers' fields can be improved by increasing uptake of soil N as well as by enhancing AE and PE (Cassman et al. 1998). It suggests that the buildup of soil N or soil organic pool due to the application of fertilizer N (Fig. 11.2) can contribute to an increase in NUE in subsequent years. And to achieve high NUE in a given season, it is important to adjust the dose and time of fertilizer N application as per the availability of soil N.

Reports already exist that sustained increases in organic matter, particularly in aerated soils (not under irrigated rice), lead to increased N supply from the soil due to mineralization of organic N pools and reduced fertilizer N applications can maintain both high yield levels and PFP (Bell 1993; Kolberg et al. 1999). If due to some kind of soil mismanagement, organic matter in the soil is declining over time, it can lead to loss of N from the soil N pool over and above that from the fertilizer N. It will lead to a reduction in PFP and fertilizer N doses will have to be increased to maintain optimum yield levels. In soil in South Asia containing more than 2500 kg N ha^{-1} in the 0–0.3 m depth, a crop of irrigated wheat will typically remove 110 kg N ha^{-1} at a fertilizer N application rate of 120 kg ha^{-1}. With RE of 0.40, only 48 kg N ha^{-1} comes from fertilizer, and rest 62 kg N ha^{-1} is the contribution of soil N. But at the same time, a substantial portion of the 72 kg N ha^{-1} applied as fertilizer but not used by the crop, becomes a part of the soil N. It may become available for N uptake by crops in subsequent years. If in the above example, soil is able to supply only 50 kg N ha^{-1} rather than 62 kg N ha^{-1}, to achieve the same yield and N uptake levels by wheat crop, fertilizer N rate will have to be increased to 150 kg N ha^{-1} at RE of 0.40, although RE always decreases at higher fertilizer N application levels. At high fertilizer N application rates, fertilizer substitution value of indigenous N increases substantially. Buildup of soil N through fertilizer N substitution contributes to high RE. A decrease in soil N supply reduces the overall productivity of the soil. Improved crop varieties and application of high fertilizer N rates may sustain or increase crop yields for some years, but eventually, soil health degradation due to loss of soil N reserves will result in stagnation or even decline in yield. It is an emerging challenge for intensive agriculture based on high fertilizer N inputs in most parts of the world. Fifty-year (1961–2010) global N budget based on data generated

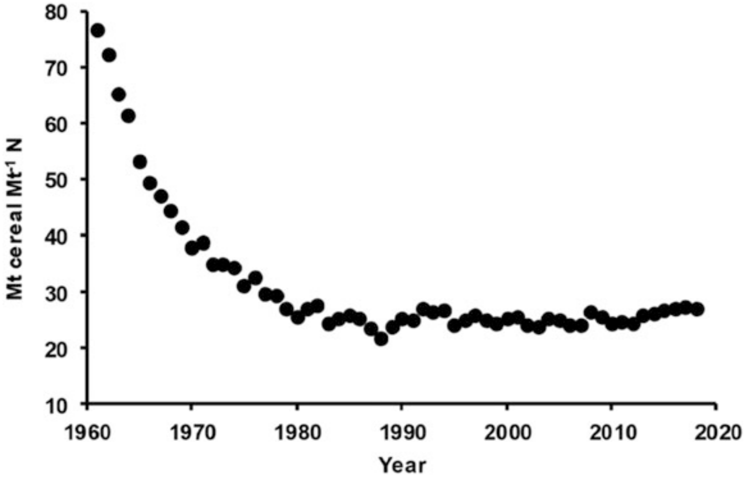

Fig. 11.3 Partial factor productivity of fertilizer N for global production of cereal grains. Data source: FAOSTAT, http://www.fao.org/faostat/en/#data/QC (Accessed 17 September, 2020)

in 114 long-term experiments being conducted in different parts of the world, revealed that soil N reserves have declined by 8% in maize and wheat production systems, but increased by 4% in rice (Ladha et al. 2016). According to Yan et al. (2014), due to continuous high fertilizer N input for the last 30 years (1980–2010) in China, RE has declined to less than 0.30 but a large portion of applied N became a part of soil N every year so that 40–68% of applied fertilizer N was utilized by the crops eventually.

As PFP is a ratio of grain yield and amount of fertilizer N applied, its large values observed at small N application rates decline with increase in fertilizer N application rates. Of course, PFP is also defined by the nature of cereal crops and achievable yield potential, soil quality, and fertilizer and crop management operations. As global fertilizer N consumption increased from 11.39 Mt. in 1961 to 108.66 Mt. in 2018, PFP in cereal grain production decreased from 77.0 kg grain kg^{-1} N in 1961 to 27.3 kg kg^{-1} in 2018 (Fig. 11.3). Until and unless the response curve for yield as a function of the amount of applied N is shifted up by removing constraints on yield through improved management, a decrease in PFP is expected when high yields are recorded following a fixed N response function. Thus, decline in PFP soon after the introduction of N fertilizers in a region was observed due to the application of increasing amounts of fertilizer N by farmers. In many developed countries in North America, Western Europe, and countries like Japan and South Korea in Asia, a steady increase in PFP has been observed since the mid-1980s because cereal yields in these countries have been increasing even though fertilizer N use has been small or even declined in some regions (Dobermann and Cassman 2005). High yields along with high PFP in these countries have been observed due to improved management practices, fertile soils, favorable climate, high yielding and stress-tolerant cultivars, and improved fertilizer recommendations (IFA 2007). In contrast

Table 11.5 Different fertilizer nitrogen use efficiency indices for rice, wheat and maize. Average values as reported by Ladha et al. (2005) are based on data obtained from 93 published studies conducted all over the world

Crop	Fertilizer N rate (kg N ha^{-1})	AE[a]	RE[b]	RE (^{15}N)[c]	PE[d]	PFP[e]
Maize	123	24.2	65	40	36.7	72.0
Rice	115	22.0	46	44	52.8	62.4
Wheat	112	18.1	57	45	28.9	44.5
Average		20.6	55	44	40.6	51.6

Source: Modified from Ladha et al. (2005)

[a] AE = agronomic N use efficiency (kg grain increase kg^{-1} N applied)

[b] RE = recovery efficiency of fertilizer N (% of N applied)

[c] RE (^{15}N) = recovery of ^{15}N-labeled fertilizer N (% of N applied)

[d] PE = physiological N use efficiency (kg grain increase kg^{-1} N taken up)

[e] PFP = partial factor productivity of N (kg grain yield kg^{-1} N applied)

to developed countries, fertilizer N use in the 1960s was very low in developing countries but after the Green Revolution fertilizer N application rates increased rather exponentially. This resulted in a sharp decrease in PFP; at rates of almost −1 to −2% $year^{-1}$ (Dobermann and Cassman 2005). However, Africa is an exception with very high PFP values indicative of unsustainable soil N mining. No reports are yet available which document country-scale increase in PFP due to the adoption of improved N management strategies in developing countries.

Ladha et al. (2005) carried out a worldwide evaluation of NUE in cereal-based systems and based on data generated in 93 published studies, reported average values of RE, PE, AE, and PFP for fertilizer N in rice, wheat, and maize. As shown in Table 11.5, both AE and PFP were the smallest in wheat and the largest in maize. The differences in PFP are ascribed to large economic outputs of maize and rice as compared to that of wheat as well as inherent N concentration in grains of the three crops: 9–12 g N kg^{-1} rice, 13–14 g N kg^{-1} maize, and 16–18 g N kg^{-1} wheat (Ladha et al. 2005). The average RE values were 0.65, 0.46, and 0.57 for maize, rice, and wheat, and these were higher by 25%, 2%, and 12% than the RE values measured by using ^{15}N-labeled fertilizer, respectively. The smallest RE values for rice among the three crops were caused by anaerobic conditions in which rice is grown as well as due to application of reduced forms of N in rice, which favors loss of applied N via ammonia volatilization and denitrification (Cassman et al. 1998). For cereal grain production, Raun and Johnson (1999) gave a worldwide average RE of 0.33. According to Ladha et al. (2005), it is likely that for rice, wheat, and maize, RE under rainfed conditions ranged from 0.20 to 0.30, and for crops grown with assured irrigation the range was from 0.30 to 0.40. The largest average values of PE for rice are due to low grain N concentration as compared to that of maize and wheat. Also with its large harvest index, rice can efficiently mobilize N from other plant parts to grains (Ladha et al. 1998). Maize shows higher PE than wheat as it is a C_4 crop and has relatively less inherent N concentration in grains (Cassman et al. 2002) (Table 11.5).

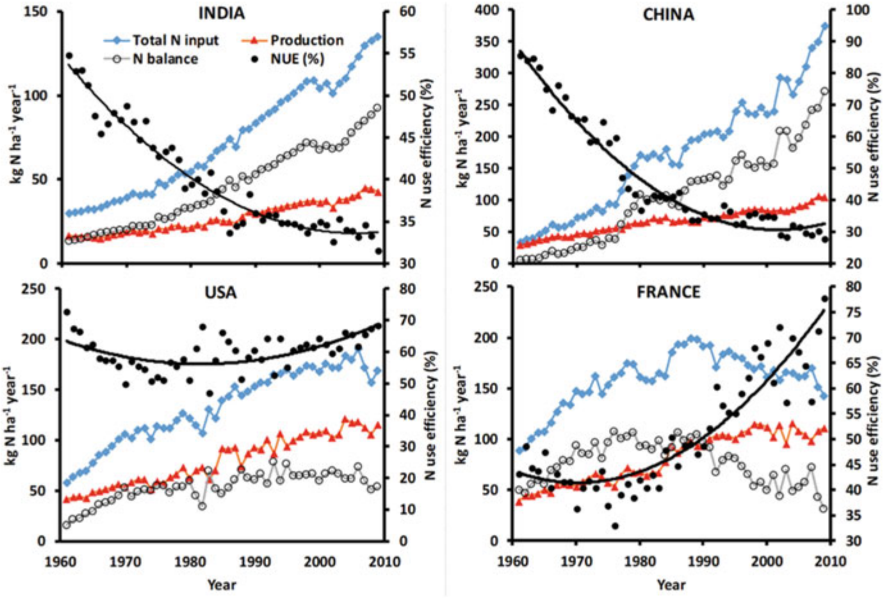

Fig. 11.4 Total N input through all sources including fertilizer, N output in economic yield of crops, N balance (difference of N input and N output), and N use efficiency (N output expressed as percentage of N input) in cropping systems in India, China, USA and France during 1961 to 2009. Data source: Lassaletta et al. (2014)

Lassaletta et al. (2014) used FAO databases to estimate total annual inputs of N to arable land through fertilizers, manures, symbiotic fixation, and atmospheric deposition, and total N output through crop yield for 124 countries of the world for the period 1961 to 2009. As both input and output of N were expressed as kg N ha^{-1} year^{-1}, these data allowed to estimate N balance as the difference between N input and N output, and NUE as the N output expressed as a percentage of total N input. Time trends for 50 years in annual N input, N output, N balance, and NUE for India, China, USA, and France are plotted in Fig. 11.4. In both India and China, total N consumption has been continuously increasing since 1961, but the rate of increase in N output in terms of yield is very low. As a result, NUE in India has fallen from 54.8% in 1961 to 31.6% in 2009 and in China from 85.6% in 1961 to 27.7% in 2009. Several developing countries like India, China, and Egypt are following the trajectories of regularly increasing fertilizer N consumption with a continuously declining crop yield response to N and rapidly falling NUE. In the case of countries like USA, fertilizer N inputs did not increase rapidly from the 1980s onwards but yields of important crops (N output) kept on increasing, though moderately. It is reflected in a consistent trend in NUE over the time achieved through improved agronomical practices even for production factors other than fertilizer N (Howarth et al. 2002; Alston et al. 2010). Time trends in NUE for France, Netherlands, and most of the West European countries are unique in terms of increase in both fertilizer

N use (N input) and yield (N output) from 1960 to 1975. However, after 1975, while yields kept on increasing, fertilizer N consumption did not increase further; N input even exhibited a decreasing trend from the 1980s onwards. These trends are clearly translated into a rapid increase in NUE of about 40% in the early 1980s to 78% in 2009 as shown for France in Fig. 11.4.

By fitting a plot of N output (yield) versus total N input to a single parameter hyperbolic function, Lassaletta et al. (2014) computed Ymax, the yield obtainable at saturating N fertilization. The Ymax values for India based on yield trends during 1961–2009 and 1995–2009 were 51 and 59 kg N ha^{-1} $year^{-1}$, respectively. Similarly for China, the values based on the periods 1961–2004 and 2005–2009 were 118 and 139 kg N ha^{-1} $year^{-1}$, respectively. Almost similar Ymax values for the two periods for both India and China suggest that fertilizer management practices in the two countries did not improve substantially since the fertilizers were introduced so that NUE is rapidly falling due to continuously increasing fertilizer N consumption (Fig. 11.4). In sharp contrast, Ymax values for USA based on the periods 1961–1979 and 1985–2009 were 130 and 269 kg N ha^{-1} $year^{-1}$, respectively, and for France the values were 103 kg N ha^{-1} $year^{-1}$ based on the period 1961–1975 and 297 kg N ha^{-1} $year^{-1}$ based on the period 1994–2009. The huge increase in Ymax values for USA and France when these were based on recent period convincingly suggest that fertilizer NUE has greatly increased by following improved management practices in these countries. In some countries such as in Africa, there are always very low N inputs as well as yields; sometimes even higher N output in terms of yields than fertilizer N input are observed. Such negative N balances constitute the signatures of unsustainable N mining scenarios in agricultural soils (Lassaletta et al. 2014).

11.5 Fertilizer Nitrogen Use Efficiency in Relation to Environmental Security

Surplus N in agricultural soils designated as N balance in Fig. 11.4 (Lasaletta et al. 2014) and defined as total N input minus N outputs, is an indicator of the potential losses of N from agro-ecosystems to different components of the environment (van Beek et al. 2003; Van Groenigen et al. 2010). When N input, N output, and N balance are expressed in units of kg N ha^{-1} $year^{-1}$, and NUE is expressed as the ratio of N output and N input, N balance is related to NUE as:

$$\text{N balance} = \text{N output} \times (1/\text{NUE} - 1) \tag{11.3}$$

Thus in the well documented (Lasaletta et al. 2014; Conant et al. 2013) first phase of agricultural expansion in different countries of the world, rapid increase in fertilizer use or N input, a moderate increase in N output or yield, and a substantial increase in N balance or surplus N was accompanied with a concomitant decrease in NUE. In Fig. 11.4, this phase is visible up to 1980s in USA and France which represent North America and Europe, respectively. India, China, and most of the

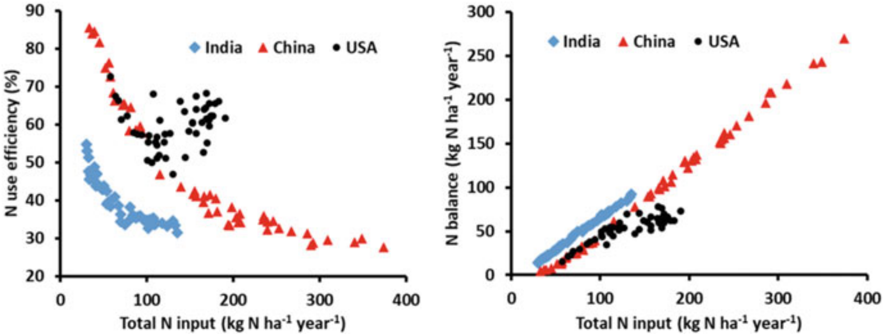

Fig. 11.5 Nitrogen use efficiency (N output expressed as percentage of N input) and N balance (difference of N input and N output) as functions of total N input during 1961 to 2009 in India, China and USA. Data source: Lasaletta et al. (2014)

developing regions of the world are still in the initial phases of agricultural intensification and with falling NUE showing increasing surplus N in the form of N balance, which is posing a potential threat to environmental security. Developed countries such as USA and France are already in the second phase of agricultural expansion which consists of sustainable intensification of agriculture being achieved by growing high yielding crop cultivars, improved water management, balanced application of different plant nutrients, adopting tools for precision and need-based application and site-specific management of fertilizers, and using enhanced-efficiency fertilizers (Houlton et al. 2019). In the second phase of agricultural expansion, while N output in the form of yield kept on increasing, applied N and surplus N, either declined (as in the case of France in Fig. 11.4) or did not increase appreciably (as in the USA) while NUE showed an increasing trend. Countries like India and China and most of the developing countries are yet to enter the phase of sustainable intensification of agriculture.

In Fig. 11.5, NUE and N balance are plotted as a function of N input for India, China, and the USA. Although total N input did not exceed 150 kg N ha^{-1} year^{-1} in India, NUE was conspicuously less than both USA and China. As explained in the previous section, it is because of soil and climate constraints as well as inadequate fertilizer management that the potential for obtaining high yields (Ymax) in India (59 kg N ha^{-1} year$^{-1)}$ is lower than both China (139 kg N ha^{-1} year^{-1}) and USA (269 kg N ha^{-1} year^{-1}). In accordance with trends in NUE values, the highest N balance or potential for loss of N from agricultural soils to the environment was observed in India, followed by China, and the least in the USA (Fig. 11.5). These data convincingly show that achieving high NUE values in agro-ecosystems is a must for controlling environmental degradation due to increasing fertilizer N use in crop production.

Modern agriculture strives to achieve food security on a sustainable basis both at country and global scales but not at the cost of environmental security (Foley et al. 2011). According to Dobermann and Cassman (2005) and Ladha et al. (2016), until and unless NUE is substantially increased in farms all over the world, fertilizer N consumption will have to be increased by about 60% to produce enough cereal grains to meet the global demand but it will lead to major environmental issues. Recently, Lu et al. (2019) studied the role of fertilizer N use in the USA in defining state-level NUE for maize and wheat and reported that in recent decades it was due to an increase in NUE for the production of the two crops which resulted in reduced losses of N from agriculture. They further observed that N surplus in agro-ecosystems was reduced due increase in N uptake and productivity of maize and wheat. While discussing strategic options for policy coordination on a global scale, Houlton et al. (2019) emphasized that by rapidly improving NUE of food production there will be an economic benefit to farmers as well as reduced N-based global warming, air, and water pollution.

11.6 Economic Aspects of Fertilizer Nitrogen Use Efficiency

Economic models dealing with carbon issues on a global scale (Rockström et al. 2017; Meena et al. 2020) have not yet been perfected to optimize N solutions although excess N has already caused substantial economic damage. Clear public policies are still lacking in several countries leading to a reduced appetite for technological breakthroughs. According to Houlton et al. (2019), policies and pricing mechanisms on N-related social costs can spur appropriate innovations to use N for producing enough food for the masses but with minimal environmental costs.

The ratios of fertilizer to crop prices (Rfc) are useful not only in guiding farmers regarding the application of fertilizer at levels that give them optimal economic returns but also in making decisions about technologies and nutrient management practices, which influence NUE and surplus N in agro-ecosystems (Zhang et al. 2015b). Since adequate amount of data were available for maize, Zhang et al. (2015a) studied the role of the cost of fertilizer and selling price of the farm produce (effect of government subsidies included) in influencing management decisions on the farm. They found that Rfc for maize is positively correlated with NUE. As maize prices in the USA follow the same trend as the price of other major crops, historical values of Rfc for maize were also found to be significantly correlated with NUE aggregated for all other crops. Van Grinsven et al. (2015) reported that in both France and USA, increases in Rfc since 1990 are closely related to increase in NUE. On the other hand, in both India and China, Rfc has been continuously declining due to heavy subsidies on fertilizer prices (Singh and Narayanan 2015; Li et al. 2013). In fact, globally the largest amount of surplus N in agro-ecosystems and the lowest national average NUE values have been reported from China. India also is showing similar NUE levels and accordingly high proportion of N input as surplus N (Fig. 11.4). Due to low Rfc values in countries like India and China, farmers have developed the tendency to sustain high crop yields by keeping increasing fertilizer N application levels instead of exploring and adopting efficient fertilizer N management strategies. In most of the countries in Africa, where fertilizers are very expensive for smallholder farmers, fertilizer subsidies can play a positive role in boosting the low yield levels and reversing the small or negative N surplus (soil mining) in agricultural soils (Zhang et al. 2015a). In African countries, significant increases in fertilizer N inputs will hugely increase crop yields with little risk of much N leaving the soil–plant system and polluting the environment.

11.7 Improving Fertilizer Nitrogen Use Efficiency

Analysis carried out by Zhang et al. (2015a) shows that if global food security and environmental stewardship are to be achieved by 2050, the average RE in agricultural production systems will have to be increased from 0.40 to 0.70. Awareness is already growing to achieve the target although technological and socio-economic opportunities to improve different indices of NUE vary among regions and countries. To effectively reduce losses of reactive N from agro-ecosystems while maintaining an adequate rate of increase of cereal grain production to meet the food demand of the burgeoning global population, increases in both PFP and RE are to be ensured through innovative crop and soil management practices. Adequate emphasis is also being laid on improving PE because of its impact on grain yield through translocation of N into grains in relation to fertilizer N input (Cassman et al. 2002). Knowledge-based N management plays an important role but only the generation of appropriate technologies and strategies is not enough. Socio-economic incentives, as well as removal of obstructions for adoption of proven technologies and management options are equally crucial to help farmers achieve high levels of different indices of NUE (Davidson et al. 2015).

The rooting system of vigorous crop plants efficiently uses both indigenous and fertilizer N to produce optimum yields, which contribute to improvement in NUE. In this context, efficient uptake and utilization of applied N (improved RE and PFP) and efficient translation of N to grain yield (improved PE) can be achieved by ensuring adequate crop health, appropriate climate and soil moisture conditions, balanced application of N with other nutrients, use of improved cultivars and hybrids, and management of insects, pests and weeds. Thus, in a well-managed crop, optimum RE and profits can be recorded when the soil mineral N pool is maintained at the optimum size to meet the N requirements of the crop throughout the season (Fig. 11.2). While too little N in the mineral N pool leads to reduced profits, too much N in the pool results in losses of N from the soil–plant system (Cassman et al. 2002).

Several reviews including those by Ladha et al. (2005), Fageria (2014), Davidson et al. (2015), Prasad and Hobbs (2018), and Houlton et al. (2019) have emphasized that improvement in NUE can be achieved by adopting a mix of technologies and strategies managing fertilizers, soils and crops. The efficient N management strategies revolve around fertilizer N rates which are optimum for the crop, appropriate methods and timings of fertilizer N application, and correct placement of N in the soil. In recent decades, the use of enhanced-efficiency fertilizers which include controlled-release fertilizers as well as the use of urease and nitrification inhibitors with conventional N fertilizers, integration of different sources of N (fertilizers, manures, and/or crop residues), and site-specific management of fertilizer N to achieve improved synchronization of N supply with N uptake by crops are being used to achieve high NUE in different crop production systems. The "four rights" or simply the *4Rs* of fertilizer N management: *right rate, right type, right placement, and right timing* (Johnston and Bruulsema 2014; Zhang et al. 2015a) constitute the most important strategy to improve NUE, but the 4Rs best management practices are not simply a universal set of recommendations. Considering the variability that generally exists in agricultural farms, defining 4Rs for a crop in a given field, location or region is not easy. Ideally, 4Rs for fertilizer N is very site-specific because N supply to crop plants is governed by soil N to a great extent even when optimum levels of fertilizer N are applied (Chien et al., 2009; Yadav et al. 2020). Further, it is essential to achieve a balance among the 4Rs because these are interconnected and are also governed by the overall management practices followed in the agro-ecosystem. If any one of the 4Rs is not correct, the remaining ones also cannot be right. Many times farmers overemphasize the fertilizer N rate because it is directly linked with cost. Therefore, source, time of application, and placement of fertilizer N in the soil offer opportunity for improving NUE. There can be several right combinations of 4Rs for fertilizer N at a given location and crop. However, when one of the 4Rs is changed, the others need to be adjusted accordingly.

Enhanced-efficiency N fertilizers constitute promising management options to improve NUE. These products include slow-release and controlled-release fertilizers and fertigation technologies, which precisely deliver nutrients as per need of the crop, and amendments, which alter microbial transformations in favor of increased N availability to crop plants (urease and nitrification inhibitors and N stabilizers). In a meta-analysis based on studies carried out in China during 2000 and 2016, Ding et al. (2018) reported that by applying slow-release fertilizers in rice average increases in RE, AE and PFP were 34.8%, 29.5%, and 6.3%, respectively, over the values recorded for water-soluble fertilizers like urea. Zhang et al. (2019) conducted a meta-analysis using 866 observations from 120 studies and found that application of controlled-release urea to maize increased average yield by 5.3% and NUE by 24.1% as compared to when urea was applied to supply the same level of N. Using controlled-release fertilizer rather than ordinary urea also resulted in a significant reduction in nitrous oxide emission, N leaching, and ammonia volatilization by 23.8%, 27.1%, and 39.4%, respectively. Greater improvement in NUE and higher reduction of nitrous oxide emissions by applying N through controlled-release urea fertilizer were observed at medium ($150 < N < 200$ kg N ha^{-1}) and high N rates ($N > 200$ kg N ha^{-1}) than at low fertilizer N application rates. Abalos et al. (2014) conducted a meta-analysis of 27 studies (21 for NUE) to evaluate the effect of applying nitrification and urease inhibitors (DCD, DMPP, and NBPT) yield and NUE of different crops. It was observed that grand mean effects were 7.5% and 12.9% increase in crop yield and NUE, respectively.

During the last two decades, improvement in NUE in crop production systems has been recorded by achieving greater synchrony between N supply from all sources including fertilizer and N demand by the crop throughout the growing season (Cassman et al. 2002). The site-specific management of fertilizer N revolves around the utilization of both fertilizer N and soil N but takes into account the spatial and temporal variability in crop responsiveness to fertilizer N. Losses of N from the soil are also taken care of by the site-specific N management. It is emerging as an important strategy for improving NUE in different cereal crops (Diacono et al. 2013; Witt et al. 2007; Franzen et al. 2016; Peng et al. 2010; Bijay Singh et al. 2020). Bijay Singh and Singh (2017a, b) have reported significant increases in different indices of NUE in rice in developing countries when rather than the general recommendations for the region, site-specific N management based on mid-season measurement of plant N status using chlorophyll meter or leaf color chart was practiced. In large fields in developed countries, variation in soil N supply is taken care of by using on-the-go variable rate N-fertilizer applicators (Inman et al. 2005). Delineation of soil management zones and soil mapping is also being used to improve NUE. Process-based, dynamic crop simulation models can also be used to achieve synchronization between plant N demand and N supply in the soil from different sources including fertilizer (Zhang et al. 2012).

Keeping in view the global fertilizer N consumption scenario, NUE can be significantly enhanced by using fertilizer N where it is needed the most (Houlton et al. 2019). While farmers in a large number of countries have affordable and easy access to N fertilizers, still several countries such as sub-Saharan Africa lack access to adequate amounts of fertilizer N (Wang et al. 2017). Improving the availability of fertilizer N in these countries through intergovernmental cooperation and policies and using efficient and technologically advanced approaches will not only ensure an increase in overall NUE but also reduce famines and promote resilience.

It is not that NUE improvements can be made only by adopting new technologies. It is possible to make large gains even by the widespread adoption of the existing technologies. Using less fertilizer N by improving NUE has two incentives—economic gains and reduced N pollution. When new technologies for improving NUE are offered, adoption by farmers is not likely if these will not be able to ensure adequate economic returns to the farmers. In many countries, complex socio-economic factors affect the decision-making by farmers for adopting strategies for improving NUE. In fact, it is only recently that farmers in most of the countries have started becoming knowledgeable about NUE and it is going to be critical in improving NUE (Davidson et al. 2015). Socio-economic impediments discouraging farmers from adopting improved nutrient management practices are not only related to cost and perceived risk but also to lack of trust in the advice being provided by agricultural extension agencies. According to Zhang et al. (2015b), due to the reasons that farmers primarily act to maximize their profits, and because incentives to adopt new technologies and management practices are limited, new technologies will not always result in reduced N pollution. Zhang et al. (2015b) developed an NUE economic and environmental impact analytical framework and by following it concluded that technologies that do not increase yield ceilings always lead to reduced N application rates as well as reduced N losses. But adoption of these strategies does not lead to land sparing and as a result, farmers do not get encouraged to follow these. In contrast, technologies such as planting hybrids, which increase the yield levels, lead to environmental benefits in terms of sparing the land so that farmers readily adopt these due to high economic incentives. But such technologies and management practices generally result in the application of high N rates and more N losses to the environment.

11.8 Conclusions

Fertilizer N produced by Haber–Bosch process is a double-edged sword. It helped in the fight against hunger in the second half of twentieth century but created several environmental challenges for the twenty-first century. The solution lies in achieving high fertilizer NUE in agricultural systems. Although NUE simply represents the percentage of applied N, which is taken up by crop plants or economic produce that leaves the farm, it is not as simple because fertilizer N strongly interacts and mingles with a large pool of N already in the soil and only a small portion (up to ~45%) of applied N is directly used by crops plants. NUE can be expressed in the form of AE, RE, PE, and PFP, but PFP and RE are the most useful indices for fertilizer N applied to produce high yields with minimal loss of N to the environment. Improving NUE in agro-ecosystems is of enormous importance and represents a great research challenge because increasing demand for food and fiber cannot be fulfilled without applying fertilizer N and surplus N (applied N more than removed via economic yield) can become a potential threat to the environment.

India, China, and several other developing countries are yet in the initial phases of agricultural intensification characterized by a rapid increase in fertilizer N use, moderate increase in crop yield, and substantial increase in surplus N, and accompanied by a concomitant decrease in NUE. This phase lasted up to the 1980s in developed countries in North America and Europe. These countries are already in the second phase of agricultural expansion in which yields are increasing but N input through fertilizer and surplus N either declined (as in Western Europe) or did not increase appreciably (as in the USA) and NUE is showing an increasing trend. Ensuring high NUE values in agro-ecosystems is a must for controlling environmental degradation due to increasing fertilizer N use for crop production.

The ratio of fertilizer to crop prices constitutes an important factor in deciding fertilizer N application rates to produce crop yields that will give optimal economic returns and is also positively correlated with NUE. With the availability of heavily subsidized fertilizers in developing countries like India and China, the low fertilizer to crop price ratios are resulting in very low NUE values and large surplus N in the agricultural soils. Farmers in these countries prefer to increase crop yields by applying more fertilizer N rather than exploring and adopting efficient fertilizer N management strategies.

Knowledge-based N management is already playing an important role in improving NUE and reducing surplus N in developed countries in Europe and North America but cultural and socio-economic incentives and impediments are proving crucial for the adoption of technologies and fertilizer N management strategies by farmers for achieving high NUE in most of the developing countries. The efficient N management strategies to improve NUE revolve around optimum N rates, appropriate methods and time of application, and correct placement in the soil of fertilizer N. These are increasingly being achieved through the development of enhanced-efficiency fertilizer materials, integrated use of fertilizers and organic N sources, and site-specific N management to achieve improved synchronization between the requirement of N by crops and supply of N from all sources. Nevertheless, it is also possible to make large gains in NUE by the widespread adoption of the existing technologies.

New technologies or strategies for improving NUE, which do not increase yield ceilings result in reduced N applications as well as reduced surplus N, are generally not welcomed by farmers because they cannot spare land. Technologies that increase yield levels are preferred by farmers but these require high N application rates and may lead to high N surplus as well. Significant new investments and partnerships between farmers, scientists, economists, citizens, and industries will be required to overcome technical, economic, and social impediments to improve NUE in current and future agricultural systems to meet society's food and environmental security.

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Phosphorus Availability in Soils and Use Efficiency for Food and Environmental Sustainability

12

Pritpal Singh, Rajan Bhatt, and Gagandeep Kaur

Abstract

Phosphorus (P) is indispensable for all life forms and is known as 'king-pin' in world agriculture. In spite of its high P concentration in most soils of the world (~100–3000 mg P kg^{-1} soil), P is the most deficient nutrient in global agriculture. Its highly complex chemistry and occurrence of series of transformations on the soil colloidal complex make it the least soluble compound in soils. Phosphorus concentration in soil solution varied widely from very high (10^{-4} M) to a deficient (10^{-6} M), further extremely low in the least fertile soils of tropical regions. The minimum P concentration to which growing plant roots are exposed and P deficiency in rhizosphere occurred is ~1 μM. Aside from inherent behavior of the farmers to add more and more of the P-fertilizers being added to soils under different cropping systems, available P concentration in soil solution seldom exceeds ~5 μM L^{-1}. Phosphorus dynamics and availability in soils are significantly controlled by the soil's properties including physical, chemical, and biological. About 90% variability in organic P (Po) and inorganic P (Pi) is related to soil texture with a negative correlation with a sand content of the soil. Due to calcium (Ca^{2+}) ion activity in the aqueous phase, there occurs a formation of insoluble Ca-P minerals (viz. hydroxyl apatite (HA), β-tricalcium phosphate

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(*β*-TCP), dicalcium phosphate dehydrate (DCPD), octacalcium phosphate (OCP)) in the calcareous soils. In acidic soils, aluminum (Al^{3+}) and iron (Fe^{3+}) get attached to SOM, leading to the formation of metal-OM complexes. The soil management and crop production practices that increase soil organic matter (SOM) levels had a significant influence on P availability and its dynamics in soils. The application of organic manures either alone or conjointly with fertilizers causes a significant change in P fractions (Po and Pi) due to reduction in P sorption, conversion of non-labile P to the labile P pool, and prevention of the formation of meta-stable compounds like *β*-TCP and HA in the soil, causing a large flush of available P in the equilibrium soil solution and increased P use efficiency (PUE).

Keywords

Phosphorus release kinetics · Mineral solubility · Reaction products · Integrated nutrient management · Soil properties

Abbreviations

ACP	Amorphous calcium phosphate
ANN	Artificial neural networks
$CaCO_3$	Calcium Carbonate.
CEC	Cation exchange capacity
CDB	Citrate dithinonite bicarbonate
DCP	Dicalcium phosphate
DEM	Digital elevation model
FYM	Farm yard manures
GRNN	General regression neural network.
HA	Hydroxyapatite
IFA	International Fertilizer Industry Association
MCP	Monocalcium phosphate
MSE	Mean square error
MLR	Multiple linear regression
OCP	Octa calcium phosphate
PDE	Phosphodiesterase
PME	Phospho-monoesterase
Q/I	Quantity-intensity relationship
RP	Rock phosphate
SOC	Soil organic carbon
SOM	Soil organic matter
SPR	Standard phosphate requirement
SVM	Support vector machine

12.1 Introduction

Being the second most important plant nutrient for crop growth, phosphorus is a very important plant nutrient. It is indispensable for all life forms and is known as 'king-pin' in world agriculture. Phosphorus plays a critical role in optimizing plant growth due to its involvement in different metabolic processes viz. production of adenosine tri-phosphate, enzyme regulation, and nucleic acid and phospholipids' structural element (Bünemann et al. 2006). Being next only to nitrogen (N), P is the most deficient nutrient in global agriculture, in spite of its high concentration in most soils in the world (~100–3000 mg P kg^{-1} soil), of which a significant amount exist in organic forms (Condron et al. 2005; Richardson et al. 2005; Menezes-Blackburn et al. 2016). It is because of its complex chemistry and occurrence of series of transformations on the soil colloidal complex, making its less soluble compound in soils (Halford 1997; Singh et al. 2010). Because of highly complex interactions and biogeochemical transformations in soils, the estimation of the P release potential of soils is difficult (Maassen and Balla 2010; Kumar et al. 2018). Phosphorus gets sorbed on oxides and hydroxides, forms insoluble compounds which are often not available to the plants, and got fixed in soils (Halajnia et al. 2009). Phosphorus concentration in soil solution varied widely from very high (10^{-4} M) to a deficient (10^{-6} M), to extremely low (10^{-8} M) in very low fertility tropical soils (Syres et al. 2008). The minimum P concentration to which growing plant roots are exposed and P deficiency in rhizosphere occurred is ~1 μM (Hendriks et al. 1981).

The most recent estimate revealed that globally ~5.7 billion ha of land has been suffering from P deficiency, a big hurdle for achievable optimal crop yields (Batjes 1997). Under most conditions, a significant portion of applied P gets fixed in soils as primary minerals, or as organically complexes form, and thereby, only ~1.5% to 11% remains available to growing plants for their requirement (Menezes-Blackburn et al. 2018). Even after the addition of higher inputs of P-fertilizers in texturally divergent soils, available P concentration in soil solution seldom exceeds ~5 μM L^{-1} (Wang et al. 2015). In addition, apatite mineral which is a basic input for the P industries are limited and may finish within~100 years, if used in the same extent (Stevenson and Cole 1999). Therefore, improving P use efficiency (PUE) has overwhelming significance as that of N use efficiency (Saini et al. 2019). The United States Geological Survey estimated the world rock phosphate (RP) reserves are ~18,000 million tons (Mt), while resources were ~ 50,000 Mt. (Jasinski 2006). The International Fertilizer Industry Association (IFA) estimated world RPuseof~171 Mt. in 2005 (Prud'homme 2006). With this rate of usage, the P reserve exploited between 600 and 1000 years (Isherwood 2003; Sattari et al. 2012).

Phosphorus dynamics is considered to be influenced by different mechanisms viz. dissolution-precipitation, sorption-desorption, and mineralization-immobilization reactions, etc. (Frossard et al. 2000; Manning et al. 2006) (Fig. 12.1), which is governed by various soil physicochemical properties of soils (Griffin and Jurinak 1973; Sharpley et al. 1984; Tunesi et al. 1999; Pant et al. 2002; Singh and Singh 2007a; Singh et al. 2020a; Kumar and Meena 2020). Soil P availability and use efficiency of applied fertilizer-P depends upon its dynamics in relation to soil

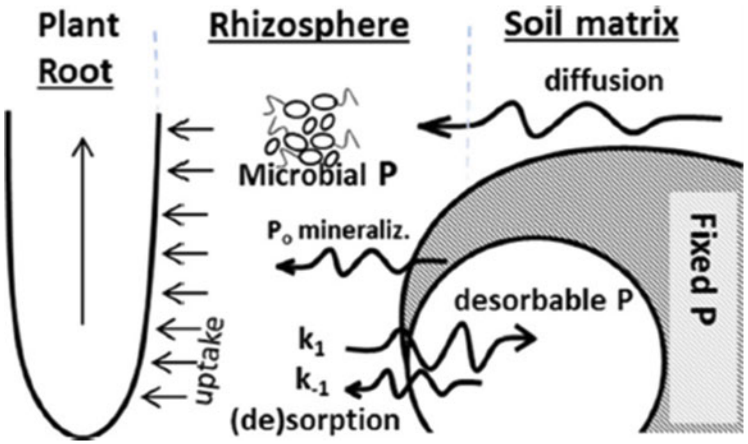

Fig. 12.1 Rhizosphere processes involved in soil phosphorus bioavailability and plant uptake different mechanisms

management and crop production practices (Reddy et al. 1999; Singh et al. 2020b; Saini et al. 2021). Practices responsible for a hike in inherent soil organic matter (SOM) levels had a significant influence on P availability and its dynamics in soils (Messiga et al. 2012). The application of organic manures increases soil organic carbon (SOC) concentration (Benbi et al. 2016), due to enhanced soil microbial biomass (Singh and Benbi 2018; Sharma et al. 2020a) and enzymatic activity (Sharma et al. 2020b) which significantly impacts the P availability (Chen et al. 2003a; Sigua et al. 2009; Sharma et al. 2020b; Singh et al. 2020b). Manure application to the soil along with inorganic P fertilizers causes a significant change in P fractions (viz. organic P and inorganic P) (Singh and Singh 2011; Ranatunga et al. 2013), reduction in sorption (Varinderpal-Singh et al. 2006; Song et al. 2007; Singh and Singh 2007b), P release kinetics (Singh and Singh, 2016; Saini et al. 2021), conversion of non-labile P to the labile P pool (Hundal et al. 1988) and prevention of the formation of meta-stable compounds like β-tricalcium phosphate and hydroxyapatite (HA) in the soil (Toor and Bahl 1999; Singh et al. 2010). Therefore, for compiling information on different soil management factors affecting the fate of applied fertilizer-P in the soils with special focus to improve its use efficiency in the global agriculture for the long-term sustainability of the agricultural production systems, the present chapter is compiled.

12.2 Crop Response to Fertilizer-P Application

Phosphatic fertilizers are generally applied in higher quantities than the plant requirement for increased land productivity and higher economic returns, which accumulate in the soils because of strong adsorptive forces, quicker precipitation, and immobilization into fixed forms from where it becomes unavailable to the plants.

Due to complex soil properties, most techniques to solubilize the recalcitrant P of soils become inefficient (Menezes-Blackburn et al. 2016). It got fixed in the soil along with slow diffusion and its availability to the roots is the most important area of interest nowadays (Ramaekers et al. 2010; Shen et al. 2011; Kumar et al. 2021). Due to low availability, P has been recognized as a major yield-limiting factor, more particularly for the developing or undeveloped countries which are facing a financial crisis and generally having lower grain yields (Lynch 2007; Richardson et al. 2011; Richardson and Simpson 2011; Meena et al. 2020). For that reason intensive cultivation in those regions, there is a need for judicious administration of phosphatic fertilizers for increased P availability and food security of projected ~9 billion human population by 2050 (Richardson et al. 2011).

From fertilizer-P application to P uptake by the plant roots, a significant portion is lost with environmental and ecological implications (Cordell et al. 2009a, 2011; Tirado and Allsopp 2012). About 1/3rd of applied P lost both due to poor management practices and by land degradation process including soil erosion (by water or wind), as only ~15–30% of applied P is used by the plants in their metabolic activities during the first growing season. The poor management practices viz. preparation of manures in open heaps might cause P loss up to the tune of ~50% to the environment (Tirado and Allsopp 2012). The mechanisms by which soil P becomes available to the plant's roots viz. diffusion, desorption, mineralization rate, etc. still required an abrupt mindset change of researchers (Menezes-Blackburn et al. 2016).

In general, its use efficiency in crop production is partitioned into PAE (P acquisition efficiency) and PUE (Manske et al. 2001; Veneklaas et al. 2012). The PAE is the capability of the agricultural crops to consumed P from the rhizosphere is referred to as PAE, while PUE is related to the ability to produce per unit of grains from every unit of P fertilizer (Hammond et al. 2009; Wang et al. 2010; Singh et al. 2020b). The dependency of PAE and PUE in improving the P availability to plants depends on several factors viz. soil, crop, and environmental (Wang et al. 2010). For sustainably reducing the P loss from the food chain and to improve the PUE, different response strategies are required in an integrated approach (Schroder et al. 2011). As per one estimate, up to ~70% of the global P demand could be met through enhanced PUE, while the remaining demand could be met through a higher resurgence and P use from its sources (Cordell et al. 2009b).

12.3 Factors Affecting P Availability

There are several factors affecting the availability of the soil P, which further affect the different metabolic activities and hence the growth and yields of the agricultural crops which are explained as below.

12.3.1 Soil pH and P Availability

The most important factor which affects the availability of P in the rhizosphere through soil solution is the pH of any soil. After extensive P uptake, mostly its concentration in soil solution was reduced, particularly under alkaline conditions (Chen and Barber 1990b). In calcareous soils, P gets precipitated as calcium phosphates (Ca-P) having extremely low solubility. Under low soil pH conditions, P gets precipitated as phosphates of Fe or Al (viz. Fe-P and Al-P, respectively) with lesser solubility. For better crop response of applied P, a pH range of 6.0–7.0 is considered important. The reclamation of the acidic or alkaline calcareous soils lead to increased P availability and therefore, crop response due to increased H_2PO^- ions in soil solution is related to easy absorption by the plants. The concentration of P in soil solution in ionic form decides its availability to plants roots. The $H_2PO_4^-$ and HPO_4^{2-} ions in the soil solution constitute the main form absorbed by the plant roots (Shen et al. 2001). The predominance of HPO_4^{2-} ions in a soil solution occurred between soil pH = 7.5–8.2, and preferential uptake of $H_2PO_4^-$ by plants compared to HPO_4^{2-} results in its reduced availability in alkaline soils. The activity of $H_2PO_4^-$ plays a greater role in determining P uptake by the roots (Hagan and Hopkins 1955). Sentenac and Grignon (1985) reported that increasing pH above 5–7 gradually diminishes $H_2PO_4^-$, while increases the concentration of HPO_4^{2-} ions. The $H_2PO_4^-$ is absorbed by the plants ~10-times more rapidly than the HPO_4^{2-} form; therefore, P availability would be greater at low pH values unless other factors inhibited root growth (Chen and Barber 1990a). At pH >9.0, the release of more P would occur due to the effect of associated cations. Because at this pH, the proportion of $H_2PO_4^-$ ions would significantly decrease, while on the other hand the proportion of HPO_4^{2-} ions would increase manifold (Tisdale and Nelson 1975). Tunesi et al. (1999) revealed that when increasing amounts of exchangeable cations such as Ca exceeds the solubility products for the P solid phase, which produces higher P removal from the solution is highly influenced by H^+ ion concentration in the soil solution. The lower phosphorus solubility in calcareous soils at near-neutral pH has been reported frequently (Gardner and Kelley 1940; Padmavathi-Devi and Narsimham 1978). Min-Zhang et al. (2001) delineated that increase in soil pH of Spodosols, Alfisols and Entisols leads to a shift in the P solubility reactions more particularly under the light-textured soils having sand fraction on the higher side. Quang et al. (1996) highlighted a negative correlation between P sorption capacity and pH of the soils. The PO_4–P sorption is increased under relatively acidic conditions, and PO_4^-–P precipitation as Ca-P under alkaline conditions due to higher pH largely affects its availability to the plant roots (Goldberg and Sposito 1984). The amorphous calcium phosphate, octa calcium phosphate, and apatite are important Ca-based phosphatic compounds formed in near-neutral calcareous and alkaline soils.

12.3.2 Organic Matter of Soil and P Availability

Inherent organic matter of soil is the vital factor responsible for P availability and good soil health. The build-up of SOM improves the availability of essential plant nutrients, even under deficient conditions. The soils with higher SOM contents had a higher fraction of organic P in nature, which get mineralized to readily available P form in the soil solution for their uptake by the plant roots. Soil organic matter binds the Fe due to its chelating nature and prohibits the formation of insoluble Fe-P, which are unavailable to the plants even when fertilizer-P is applied. The frequent use of organic manures in alkaline soils not only improves P supply but also increased the availability of mineral forms of Pin the soil upon decomposition. Generally, the critical P concentration for optimum plant growth varies near to 0.2 μg P ml^{-1} (Fox and Kamprath 1970). In calcareous soils, SOM and orthophosphates compete for the exchange site on the highly reactive calcium carbonates ($CaCO_3$) surfaces (Halford and Mattingly 1975). The adsorption of organic materials on the sorption sites reduces the bonding energy of the adsorbed P, which reduces the plant P requirements for their optimum growth. The application of organics manures to soil leads to an increase in the soil macro-aggregate and mineral associated C (Benbi et al. 2016; Sharma et al. 2020a), which also influences P availability and related dynamics (Messiga et al. 2012; Singh et al. 2020b). The increase in inherent SOM with integrated nutrient management improves biomass and their activities (Sharma et al. 2020a, b), and improves P status in the soils (Chen et al. 2003a; Sigua et al. 2009). Organic manure application along with inorganic P fertilizers causes a significant improvement in organic (Po) and inorganic P (Pi) fractions (Ranatunga et al. 2013; Yadav et al. 2020) and reduction in P sorption (Prasad and Mathur 1997; Varinderpal-Singh et al. 2006; Song et al. 2007; Singh et al. 2010; Singh and Singh 2016). The soil management practices that involved higher addition of SOM thorough crop biomass like in agroforestry systems (Jalali and Ranjbar 2010), lead to relatively higher MBC in the soils under poplar-based agroforestry compared to intensive cereal-based cropping system (Benbi et al. 2012). The accumulation of leaf litter in soils under agroforestry affects the soil P availability by mineralization of Po (Prakash et al. 2018).

The improvement in soil microbial activity and the formation of Po occur with an increase in SOM content in soils (Dalal 1979). Increased P availability in the soils accelerates P cycling through enhanced biological quality due to increased microbial activity and associations with mycorrhiza with tree species. Inter-cropping as in agroforestry system helps release P from recalcitrant P pools, making it available to the crops. The higher availability of the available Po compared to the total P in soils under agroforestry systems was because of better land use and the addition of higher quantity of plant-mediated biomass (as litters, leaves, etc.) in soils as compared to any other conventional system. The increased microbial biomass plays a major role in P turnover by affecting its transformation and redistribution into different Po and Pi forms (Stewart and Tiessen 1987). A linear relationship between Po content and SOM in calcareous soils has been reported by Sharpley et al. (1989). Shaheen et al.

(2007) observed that Olsen-P was relatively higher in soils with greater SOM content, which was further strengthened by better relation between Olsen-P and SOM content (Trivedi et al. 2010). SOM controls the short-and long-term P availability in the soils and therefore to growing plant roots (Runyan and Dodorico 2012; Singh et al. 2020b).

Jiang et al. (2006) studied SOC and P interactions under seeded alfalfa fields in China and reported that number of growing years results increased SOC, total P, and available P. SOC was significantly positively correlated with total P, available P, and soil total N ($r = 0.627^{**}$, 0.691^{**}, and 0.546^{*}, respectively). Zhang et al. (2012) observed that the amounts of P released from the soils showed a linear positive correlations with the Po content, indicated that Po can easily release P and thereby enhanced P availability in soil solution. Hadgu et al. (2014) reported negative trends between P availability in soils to the plant roots if SOC declined below critical levels as then SOM may compete with P for adsorption sites.

12.3.3 Dominant Clay Type, Soil Texture, and P Availability

In the different soil primary particles, only clay fraction has been chemically active which results in different reactions in the soils. For P availability, clay holds a special place as it fixed the P and reduces its availability to the plants. The soils with lesser clay content have better availability of P as compared to the soils with higher clay percentages. Among different clay types, 1:1type clay (Kaolinite) has a higher P fixation capacity relative to 2:1 type clays (montmorillonite, illite vermiculite, etc.). Due to prevailing harsh weather conditions of tropical regions, much of the P got fixed due to the dominance of the Kaolinite type of clays in the soils. It has been well established that differences in P content are accompanied by variation in soil texture, with total P varied inversely to grain size (Johnston et al. 1997). Soil with higher organic matter content has been reported to supply higher amounts of P. Generally, higher quantum of amorphous Fe and Al oxides in fine-textured soils with higher SOC leads to sorb soil P (Richardson 1985; Sah et al. 1989; Lockaby and Walbridge 1998). Fixation of applied fertilizer-P happens due to the presence of higher amounts of clay, Al, Fe, and sesqui-oxides (Doddamani and Seshagiri-Rao 1989). The higher adsorption capacity of the soils with higher clay content has been reported (Bahl et al. 1986). On average, the higher percentage of sand content in soils will lead to higher release of P as compared to the soils with lower sand content (Bahl 1990). The phosphate adsorption release curves for silt and clay fractions from black Chernozem and Solodized soils revealed that clay fractions adsorbed 1 to 1.5 and 2 to 10-times higher P than silt fractions, respectively at the same equilibrium P concentration (Goh et al. 1986). About 90% variability in Po and Pi has been reported to be related to soil texture with a negative correlation with soil inherent sand proportions (O′ Halloran et al. 1985). Clay content of the soil has a direct relationship with the fixation of applied P causing reduced availability of P to the plant roots but is not affected much due to silt and sand content of soils (Douli and Gangopadyay 1984). Clay content of the soil was reported to be significantly related to soil P sorption

(Samadi 2006). Therefore, it could be concluded that heavy textured soils have lower available P in soil solution as compared to the comparative light-textured soils.

12.3.4 Calcium Carbonate and P Availability

Calcium carbonate ($CaCO_3$) exerts a dominant effect on the nature and properties of P in calcareous soils. It accumulates under calcareous soils and governs the P reactions in soil (Lindsay 1979) due to its adsorption and precipitation on the reactive surface of $CaCO_3$ (Cole et al. 1953; Griffin and Jurinak 1973; Freeman and Rowell 1981; Amer et al. 1955). Availability of P in the soil, to large extent depends upon the presence of $CaCO_3$ both in amorphous and crystalline forms. Generally, in the calcareous soils with highly reactive $CaCO_3$ surfaces, P reactions such as precipitation and adsorption affect the availability of the applied P-fertilizers (Cole et al. 1953; Griffin and Jurinak 1973; Freeman and Rowell 1981; Amer et al. 1955). In the soil solution of calcareous soils, activity of the Ca^{2+} ions leads to the formation of insoluble Ca-phosphate minerals (Tunesi et al. 1999). However, higher involvement of exchangeable Ca ions to P sorption than $CaCO_3$ has already been reported by Akinremi and Cho (1991). The adsorption process has been seen to be predominant at lower P ($<10^{-4}$ M) concentrations in solution (Halford and Mattingly 1975; Freeman and Rowell1981; Solis and Torrent 1989; Hamad et al. 1992), while the precipitation reaction dominates at higher P concentration (Matar et al. 1992). The P sorption capacity of calcite is apparently <0.3 μ mol P m^{-2} (Griffin and Jurinak 1973; Freeman and Rowell 1981; Borrero et al. 1988), which is about 1/tenth of natural Fe oxides (Torrent et al. 1992; Torrent et al. 1994). Freeman and Rowell (1981) observed that only ~25% of P sorbed by calcite was isotopically exchangeable within 14-days and by the time Ca-P had precipitated on the surface. By contrast, isotopic exchangeability at a similar time and equilibrium concentration was usually >40–50% for PO_4^-adsorbed on geothite and on non-calcareous soils containing high-affinity PO_4^- adsorbents like geothite, haemetite, gibbsite, kaolinite, etc. (Torrent et al. 1992; Torrent et al. 1994). Soper and El-Bagouri (1964) reported that the availability of added PO_4^- was not related to the carbonate content of the soil, but $CaCO_3$ had a very large effect on the movement of applied P. The extent of PO_4^-movement in non-calcareous soil was greater than in the calcareous soil regardless of the source of P added. The movement of P from applied fertilizer decreased with an increase in $CaCO_3$ contents in soil (Bell and Black 1970). Similarly, Sharpley et al. (1984, 1989) highlighted a reverse trend between fertilizer-P availability and fertilizer-P availability index due to accumulation of P on the surface of $CaCO_3$ in soil. Borrero et al. (1988) reported that in calcareous soil both the total apparent surface area of $CaCO_3$ and P sorption by $CaCO_3$ are relatively lower than clay, which played an important role in the P sorption. Halajnia et al. (2009) through a study on eight soils treated with two levels of inorganic P and manure reported that Olsen-P and NH_4OAc extractable Al and active $CaCO_3$ had a positive relationship with each other in P applied soils. In the floodplain calcareous soils of Indian Punjab, Singh and Singh (2007a) reported that for soils with comparatively higher $CaCO_3$ content, inflection point of isotherm that revealed that only at high equilibrium solution P concentration, the P deposition in soil was distinct. On the contrary, Ryan et al. (1985) reported negative relationship between loss of P from solution to both total and active $CaCO_3$ and observed no effect of $CaCO_3$ particle size on P retention from solution. The studies (Ryan et al. 1985; Solis and Torrent 1989) revealed that in the calcareous soils, P sorption was even more closely related to Fe and Al oxide and clay content than to $CaCO_3$ content (Castro and Torrent 1998).

12.3.5 Free and Amorphous Fe and Al Oxides and P Availability

Amorphous Al hydroxide formed as result of the weathering of clay minerals has a profound influence on P availability and sorption reactions. The activity of these free oxides and their ability to absorb PO_4^-ion decreased in due course of weathering (Araki et al. 1986). According to Bloom (1981) and Gerke (1992, 1993) Al^{3+} and Fe^{3+}gets bound to SOM to form metal-OM complexes which are considered responsible for the P fixation. Vo Dinh Quang et al. (1996) reported that the sites responsible for the high energy P sorption sites on Al oxi-hydroxides and to a lesser extent on poorly ordered Fe oxi-hydroxides (Solan et al. 1995; Wang et al. 1991; Zhang and Karathanasis 1997). Borling et al. (2001) and Niskansen (1990) reported that Al was more strongly correlated with P sorption than Fe. Similarly, Pant et al. (2002) observed that the P sorption maxima were positively linked with oxalate extractable Al and citrate dithionate-bicarbonate (CDB) extractable Al under anaerobic conditions and there was no significant relation with them. Borggaard et al. (1990) revealed that poorly crystalline Fe and Al oxides affect P sorption maximum significantly than from well crystalline Fe oxides. Brennon et al. (1994); Saini and MacLean (1965) reported that amounts of Al oxide in the soil were more important than that of Fe in assessing the PO_4^- ions adsorption capacity of the soils. Milap-Chand et al. (1995) reported a direct relation between P adsorption and cation exchange capacity (CEC), amorphous forms of Fe and Al, clay content, and SOC content in soils of north-western India. Adetunji (1997) conducted laboratory experiments in low activity clay soils of Ogun State (Nigeria) to develop the relationships between P sorption capacity and reported that CDB extractable-Fe was the most important variable accounting for ~99% of the variation in adsorption capacity. Likewise, Halajnia et al. (2009) reported increased recovery of CBD-P and found that Fe oxides play an important role in P sorption. In the recent floodplain soils of Indian Punjab, Singh and Singh (2007b) reported that in a majority of non-calcareous soils, the P fixation is generally regulated by strong attraction of non-carbonated clays The redox-sensitive Fe^{+3}oxides during anoxic conditions are subjected to reductive dissolution which could change the sorption behavior and release of Fe^{2+} and dissolved P (Heiberg et al. 2010). Several other studied also highlighted increased Fe and P concentrations in soils in relation to reduction in redox potential (Meissner et al. 2008).

12.3.6 Application of Organic Manures and P Availability

Among different sources of organic manures, farmyard manure (FYM) has a special role to play in increasing soil and water productivity through the improvement in soils' properties pertaining to physical, chemical, and biological aspects and making the nutrient available to the plants. The role of FYM on increased P availability in the P deficient soils has not been well understood particularly under tropical environments and under anaerobic conditions, though P fertilization is skipped due to prevailing anaerobic (reduced) conditions. On-farm trials carried out at the central highland of Madagascar reported high variations in the performance of FYM in terms of land productivity and P consumptive use patterns of rice where soils mostly remained under anaerobic conditions (Andriamananjara et al. 2016; Bhatt et al. 2021). The higher response of applied FYM in the inherently P deficient soils helps in maintaining soil pH and oxalate extractable P contents due to improved soil properties. Rabeharisoa et al. (2012) reported that in the anaerobic conditions, pH of soils becomes a critical indicator for P availability from the soil solution as it improves anion exchange membrane extractable P content in soils, particularly in low SOC soils. Extended microbial Fe-oxide reduction might be responsible for increased labile P with SOM application in soils with higher P fixation capacity. The isotope dilution principles generally preferred to study the soil P which was isotopically exchangeable (ratio of radioactive P to non-radioactive P in plants) and which, reflects increased amounts of labile P pools in soils labeled with radioactive $^{32}PO_4^-$ ions after FYM additions (Larsen 1952). Mineral P enhanced the above-ground biomass and P uptake by 0.35–1.62 g pot^{-1} and 1.59–5.71 mg pot^{-1}, respectively as compared to the control plots (Fig. 12.2) (Rakotoson and Tsujimoto 2020). However, the increase in biomass occurred to the tune of 0.11–0.77 g pot^{-1} with the addition of FYM. Plant P uptake increased with FYM additions relative to the control, which was related to the additive effect of FYM application to the mineral P application.

Toor and Bahl (1997) reported a gradual increase in $NaHCO_3$-P in soils amended with poultry manure (at 2×10^3 mg kg^{-1}) and incubated for 16 weeks at aerobic moisture regime (Table 12.1). In the acidic soil, $NaHCO_3$-P accumulation increased from 4.5 to 7.0 mg kg^{-1} during the initial 8 weeks of aerobic incubation. In the calcareous soil, $NaHCO_3$ concentration increased from initial 7.5 and 11.2 mg kg^{-1} during the initial 8 weeks of incubation. However, in the non-calcareous soil, $NaHCO_3$-P varied between 9.5 and 12.5 mg kg^{-1}, during the period followed by a gradual decrease with aging. However, Singh et al. (2010) reported the floodplain calcareous soils incubated with press mud application (@ 1.0%) exhibited increased $NaHCO_3$-P concentration from 9.4 to 14.3 mg kg^{-1} under aerobic (60% water-filled pore space) moisture regime during the 16 weeks of incubation. The extent of increase in P concentration in press mud amended soils was higher at nearly saturated (90% water-filled pore space), compared with the soils incubated under aerobic moisture regime (Table 12.1). Regardless of the moisture regime and press mud application, $NaHCO_3$-P concentration was higher in non-calcareous soils, compared to calcareous soils.

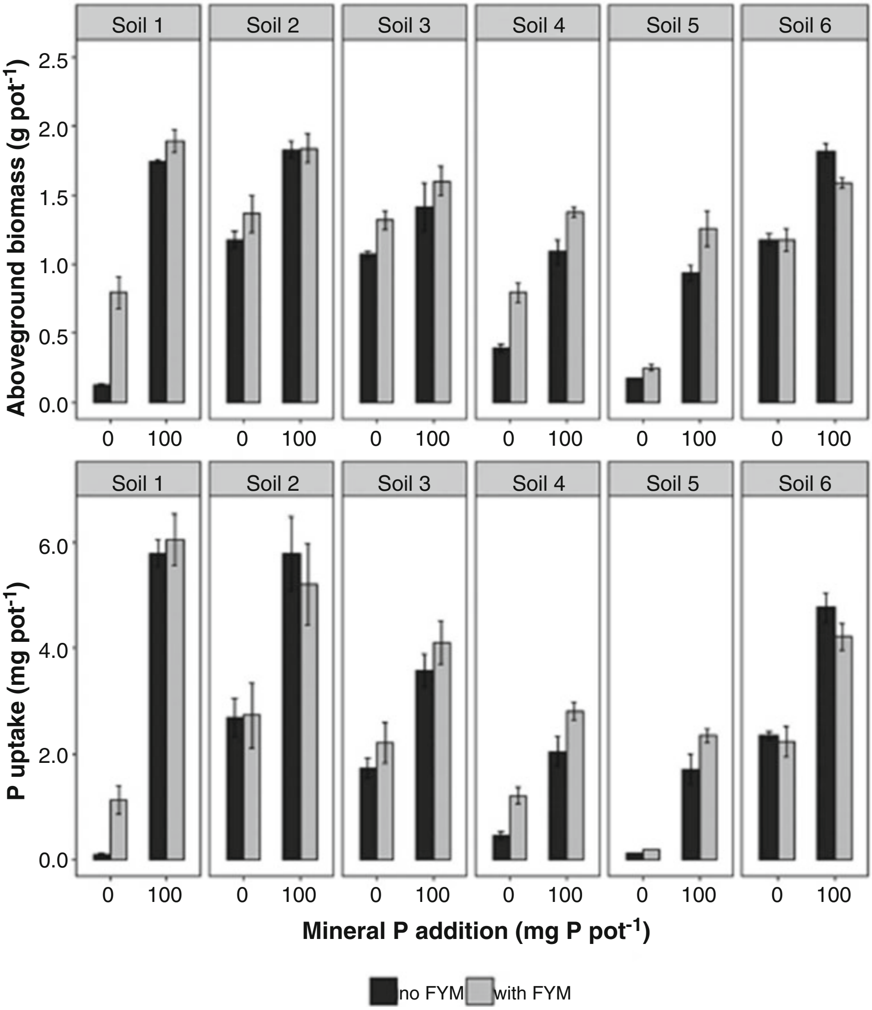

Fig. 12.2 Rice above-ground biomass and P uptake patterns under different mineral P and FYM applications (Source: Rakotoson and Tsujimoto 2020)

Organic manure application improves soil health by improving its physic-chemical properties and certainly improved the P concentration in the soil solution and ultimately has higher P use efficiencies. Vaneeckhaute et al. (2014) reported that that the sandy soil had significantly higher biomass yield and dry weight biomass yield with manure application as compared to the triple superphosphate (TSP), while the dry weight content and P content of the biomass was significantly higher than from the TSP treatment. P uptake (mg P) in the TSP treatment showed significant results as compared to the control. The PUE (dry weight yield) in the sandy soil was mostly negative as the yield of the reference TSP was lower than the control

Table 12.1 Change in $NaHCO_3$-P concentration in soils amended with organic manures under aerobic and nearly saturated soil moisture regimes

	Incubation period (weeks)						
Soil	1	2	4	8	12	16	References
Acidic (aerobic)	4.5	5.3	6.0	7.0	6.3	5.5	Toor and Bahl (1997)
Calcareous (aerobic)	7.5	8.4	9.7	11.2	9.8	8.5	
Non-calcareous (aerobic)	9.5	10.7	11.5	12.5	12.1	10.8	
Calcareous (aerobic)	9.4	12.0	12.3	12.7	13.4	14.3	Singh et al. (2010)
Calcareous (nearly saturated)	11.9	12.9	13.6	15.0	16.0	16.9	
Non-calcareous (aerobic)	12.5	16.0	16.3	16.6	17.3	18.9	
Non-calcareous (nearly saturated)	13.8	17.3	17.9	19.6	20.8	22.4	

Table 12.2 Average phosphorus use efficiency (PUE) based on the plant reaction in time (%) for the different bio-based fertilizers; PUE(control); PUE(TSP) = 100%, Fw Fresh weight; DW dry weight (^{a}TSP < control; ^{b}bio-fertilizer < control) (Source: Vaneeckhaute et al. 2015)

PUE (%)	PUE (FWyield) Sand	PUE (FWyield) Rheinsand	PUE (DWyield) Sand	PUE (DWyield) Rheinsand	PUE (uptake) Sand	PUE (uptake) Rheinsand
Struvite	—21^{a}	75	10^{a}	67	22	42
$FePO_4$-sludge	—68^{a}	159	—16^{a}	233	16	3.3
Animal manure	—46^{a}	—8.9	—8.5^{a}	—67^{b}	37	80
Digestate	—67^{a}	—45^{b}	—90^{a}	—100^{b}	80	63

(Table 12.2). Therefore, application of the organic amendments viz. farmyard manure, compost, poultry manure, etc. is reported to be best for increased average PUE based on the crop yield.

12.3.7 Soil Moisture Status and P Availability

Soil moisture content significantly impacts the P availability, mineral dissolution, and sorption and release kinetics. The soils moisture content during the rice and wheat seasons appeared totally different, which affects the P availability. But over flooded soil conditions even negatively affects the P availability (Patric and Mahapatra 1968), due to Fe oxides' reductive dissolution (Huguenin-Elie et al. 2003). Due to the re-fixation of soil P in lesser available forms under a reduced environment, P availability is reduced to a large extent (Kirk et al. 1990). In the upland crops (viz. wheat, barley, maize, etc.), the already reduced P compounds are oxidized to lesser available forms and under prolonged oxidized conditions, thereby, soil P regains its pre-flooded conditions over a period of time (Willet 1991). Under the submerged conditions, the availability of P seems to be better than the aerobic conditions. This is why P application is generally recommended in aerobic crops (viz. wheat, gram, oilseeds, barley, etc.) than the anaerobic crops viz. paddy rice. Under the submerged condition, the unavailable and fixed forms of P become available to the plants under the reduced conditions (Broeshart et al. 1965, Mahapatra and Patrick 1969; Patrick et al. 1974; Ponnamperuma 1972). This has been the reason why the response of applied P to the paddy crop appeared lesser than when applied to wheat in a rice-wheat cropping system.

Some other factors also affect P absorption by the plant roots; among them, the degree and extent of waterlogged conditions, soil properties, inherent P status of soil under consideration, and fertilizer application method (Patrick et al. 1974). Under the flooded or reduced conditions, the availability of P enhanced to some extent as the case with Fe^{+3}inositol-P which reduced to Fe^{+2} inositol-P. Being an organic substrate, cellulose after combining with inorganic P, had profound effects on improving the availability of Po. Therefore, integrated nutrient use viz. use of organic manures along with inorganic manures is always advocated to improve the availability of the soil P to the plant roots which is further reflected in its growth and yield parameters (Zhang et al. 1994).

12.3.8 Soil Enzymatic Activity and P Availability

Soil enzymatic activity has a profound influence on the P availability to the plant roots. Plant species and soil microorganisms enhance phosphatase enzymes to mineralize Po compounds. Enzymatic activity has bimodal complementary action. The phosphodiesterase (PDE) has the capability to hydrolyze complex Po compounds viz. nucleic acids and phospholipids into much simpler compounds such as phosphor-monoesters which had the capabilities to mineralize Po into the forms readily available to the plants (orthophosphate, $H_2PO_4^-$) (Rejmánková et al. 2011; Stone and Plante 2014). Through P mineralization action, these enzymes played a critical role in the plant response under the limited P status of the soils (Dakora and Phillips 2002; Burns et al. 2013; Dalling et al. 2016). For modeling P cycling, phosphatase activity is considered crucial in different models pertaining to different ecosystems (Reed et al. 2015).

Phosphorus availability might be surplus when the composts are applied as N source for partial to complete supplementation of fertilizer-N. In the phospho-compost, both organic and inorganic pools of P get solubilize through organic acids during microbial activities. The cation bound chelate to phosphatic rock by hydroxyl and carboxyl groups and finally results in soluble-P. This process is triggered by soil microbial population which produces large amounts of organic acids and humic substances, including extracellular enzymes to promote SOM degradation. Enzymatic activities during the process of decomposition are vital and provide useful information on nutrient transformations and their release kinetics. Therefore, the quantification of soil enzymatic activities is considered a useful indicator for evaluating mass turnover in composts, which affects its stability and quality (Dalling et al. 2016). Among different enzymes, phosphatase being the most important which played a crucial role in P cycling and could be used as an indicator of microbial activities which further affect the P availability to the plant roots. Phospho-diesterase (PDE) and phospho-monoesterase (PME) are the two complementary enzymes; PDE hydrolyzes the nucleic acids and phospholipids complex compounds into simple phosphor-monoesters, while PME further mineralized Po into the orthophosphate that is absorbed within the rhizosphere by soil microbes (Rejmánková et al. 2011; Stone and Plante 2014). Therefore, these enzymes played a significant role in the mineralization of Po and thus in the crop response particularly under limited P availability (Dakora and Phillips 2002; Burns et al. 2013; Reed et al. 2015; Dalling et al. 2016).

It is well established that CO_2 uptake of tropical forests is affected by phosphatase activity (Goll et al. 2012; Yang et al. 2016). Therefore, critically understanding the P mineralization process, root behavior and the bacterial community interaction, and factors affecting it are important. Only agricultural experiments provide necessary insight on the role of bacteria in P possession which needs to be extended to the tropical forests with respect to their rhizosphere (Richardson and Simpson 2011; Pii et al. 2015). The interaction of plants roots and their bacterial community enables plants to prosper in soils under P deficient conditions either by enhancing PUE or P acquisition or even both (White and Hammond 2008). Under tropical conditions, plants could efficiently be using P through metabolic nucleic acid compounds produced through P re-sorption, recycling, and reduction (Vitousek and Sanford 1984; Hidaka and Kitayama 2011). The root and bacterial function are regulated by the inherent P availability and plant species (Treseder and Vitousek 2001; Costa et al. 2006; Lambers et al. 2009; Haichar et al. 2008; Bardgett et al. 2014; Hinsinger et al. 2015). Under grasslands, the activity of phosphor-monoesterase and phosphor-diesterase are reported to be significantly higher in comparison to the adjacent forest stand (Chen et al. 2000; Chen et al. 2003b). Chen et al. (2004) reported higher activities of acid and alkaline phosphor-monoesterase and phosphor-diesterase under ryegrass in comparison to the pine seedlings.

12.4 Phosphorus Movement and Environmental Degradation

Of the total applied fertilizer-P to the plants, a major part is lost either through erosion, and/or leaching. Intensive cropping intensity and tillage frequency have been adversely impacting the environmental quality along with biodiversity due to reactive N and P (Correll 1998). For meeting the P requirements of the crop plants, ~19 Mt. year^{-1} of P from RP is being used in P fertilizer manufacture industry (Heffer and Prud'homme 2008). Soil erosion and P loss to water bodies could be decreased by using the appropriated soil conservation measures as both erosion agents viz. water and wind-affected ~12 and 4% of the total European land area, respectively (Louwagie et al. 2009). It is estimated that soil erosion in Europe has caused a loss ranged from 5–40 t ha^{-1} year^{-1} (Verheijen et al. 2009) to 10 Mg t^{-1} year^{-1} (Louwagie et al. 2009). The higher part of P fixed with the clay fraction of soil gets eroded quickly with flowing water (Quinton 2002), and about

20–30 Mg $year^{-1}$ of P is lost worldwide wide which is equivalent to15–20 kg P ha^{-1} $year^{-1}$ (Ruttenberg 2003). Both soluble and particulate forms of P are moved with water moving across the surface, and eventually to have higher bio-available P concentration in surface waters (Schroder et al. 2011). Runoff water from the catchments results in the 'Eutrophication' which started in water at a P concentration of 0.10 g P m^{-3} (Correll 1998). Normally with surface runoff, P loss is considered more important than the leaching loss of soil P; therefore, more efforts are required made to arrest the surface runoff water to lakes or other water bodies.

Reduced tillage with residue retention helps to arrest the runoff water, sloping land terracing, planting along the contour, agroforestry are some of the key soil conservation technologies recommended in sloppy landscape (Schroder et al. 2011). One best practice is to apply the P fertilizer when the soil required it under deficient conditions. The frozen or snow-covered land or dry and hard soil or waterlogged should not be applied with P fertilizer (Schroder et al. 2011). Another aspect for harvesting better PUE is to apply it where it is required, and that too near to the plant roots as it moved slowly in the field (Schroder et al. 2011). For sustainably improving the soil health, one best and effective way is to enhance the inherent SOM levels through integrated approaches. Manure P must be used to the extent possible as it not only improved the soil health but also reduces the P losses in the ecosystem. Besides, improved the PUE has a key role in maintaining ecosystems' functioning and long-term sustainability (Tirado and Allsopp 2012).

12.5 Phosphorus Fractions in Soils

Under natural conditions, soils P constituted by both Po and Pi forms, mostly unavailable to the plants (Murphy and Sims 2012). Soil P fractions are considered important for studying soil P dynamics (Chang and Jackson 1957; Hedley et al. 1982; Aulakh et al. 2003). The calcareous soils had the dominance of Pi pool which ranges from ~75–85% of total P (Jiang and Gu 1989). In the calcareous floodplain soils, Pi comprised ~92–94 of total P concentration (Singh and Singh 2007b) (Table 12.3). The Pi pool is further partitioned as Ca-P (HCl-extractable P), Fe- and Al-P (non-occluded Fe- and Al-bound P), and occluded P (Chang and Jackson 1957; Solis and Torrent 1989). Majority of Pi exists as Ca-bound forms in the calcareous soils. Jun et al. (2010) reported that Pi comprised ~52–68% of total P in calcareous soils under wheat mono-cropping. Jalali and Tabar (2011) reported that the soils under garlic, orchard, pasture, potato, leafy vegetables, and wheat cultivation had dominance of Ca-P, constituting ~61–78% of total P, while labile P was the least in abundance (<2% of total P). In barley–soybean cropping system, Zheng and MacLeod (2005) reported that plant P uptake, labile, and moderately labile Pi increased with additions of fertilizer-P. The fertilized-P is mainly retained as soil labile Pi (~43–69% of total P) followed by the other fractions viz. ~20–30% of moderately labile Pi, and ~ 7–29% of sparingly soluble-P (HCl-P + H_2SO_4-P). As clay content in the soil increased, the recovery of labile P is reduced. Wager et al. (1986) reported that recovery of applied P fertilizer as labile Pi (~48% of total P) is

Table 12.3 Literature reports on effects of different cropping systems on soil P fractions in surface layer

Cropping system	Soil type	Total P (mg kg^{-1})	Inorganic P (Pi) (mg kg^{-1})	Organic P (Po) (mg kg^{-1})	Olsen-P (mg kg^{-1})	Reference(s)
Rice-wheat	Floodplain soils, Punjab, India	242–771	170–722	9.8–55.7	5.3–13.9	Singh and Singh (2007b)
Wheat monoculture	Calcarid Regosol	753–1127	422–738		2.3–22.9	Jun et al. (2010)
Groundnut-wheat	Tolewal sandy loam soil (*Typic Ustochrepts*)	390.2	343.2	47.1	10.4	Aulakh et al. (2003)

higher, compared with the moderately labile Pi (~43% of total P) and the sparingly soluble Pi pools (~9% of total P). Aulakh et al. (2003) reported that crops removed ~21–54% of applied fertilizer-P, with rest for accumulation and for other losses which account up to ~33–64% and ~ 12–32%, respectively. Beck and Sanchez (1996) studied soils' Pi and Po pools in a highly weathered soil and reported that NaOH-Pi acts as a sink for fertilizer-P, while later pool (Po) was the source of P availability in controlled systems (with no-P fertilizer application). Beck and Sanchez (1996) reported a direct relationship with the grain yields and the P availability to the plant roots, particularly under deficient conditions. Integrated nutrient management has always proved best for improving the $NaHCO_3$, better PUE, and P uptake (Motavalli and Miles 2002). Under the integrated nutrient management, particularly under the deficient conditions, moderately labile and non-labile P pool was increased and decreased by 3-and 6-times and by ~14% and ~ 18%, respectively, compared to the control plots, where no fertilizer-P was applied (Ahmed et al. 2019).

During mineralization of SOM, the Po compounds become available to the plants which leads to higher concentration of Pi (Noack et al. 2012; Wang et al. 2012). Zhongqi et al. (2006) studied P distribution in soils with manure application as Pi forms, enzymatically hydrolysable-Po and non-hydrolyzable-Po, and reported that water soluble-P, $NaHCO_3$-P, and enzymatically hydrolysable-P_o were directly associated with applied P, while NaOH-extractable P was not closely related to the manure applied P. Application of the organic acids with lower molecular weights (@ 10 m mol kg^{-1} soil) increased the Pi and Po availability. Soil Po released by low molecular weight organic acids is derived from the soil labile Po fractions. In contrast, Pi released by low molecular weight organic acids resulted from the mobilization of the moderately labile NaOH-Pi (Fe/Al-P) and HCl-Pi (Ca-Pi) fractions in the order of citric acid (4.83 mg kg^{-1}) > oxalic acid (2.40 mg kg^{-1}) > malic acid (2.04 mg kg^{-1}). Po release by low molecular weight organic acids occurred primarily due to the dissolution of soil labile Po ($NaHCO_3$-Po) (Wang et al. 2017). Regardless of the soil textural class, the application of low molecular weight organic acids followed an order of oxalic acid (0.63–3.17 mg kg^{-1}) > citric acid (0.61–2.82 mg kg^{-1}) > maleic acid (0.52–1.76 mg kg^{-1}), results in cumulative Po and mainly labile Po ($NaHCO_3$-Po) release. Under the calcareous soil, Pi release enhanced from the HCl-Pi (Ca-Pi) fraction, where oxalic acid was most effective while in neutral and acidic soils, citric acid was most effective in releasing Pi from the NaOH-Pi (Fe/Al-Pi). Mechanism for the kinetics of Po release ascribed tothe ability of low molecular weight organic acids to mobilize the labile Po ($NaHCO_3$-Po) rather than their ability to chelate cations (i.e. Fe^{3+} and Al^{3+}) bound to Po in soil (Zhang et al. 2012). Soil texture, organic matter, and P status of soils significantly affect the P mineralization/immobilization pattern in soils (Gang et al. 2012).

12.6 Phosphorus Sorption and Release Kinetics

Phosphorus release kinetics has great significance for plant nutrition and environmental pollution because it predicts how quickly reaction approaches quasi-equilibrium (Amer et al. 1955). Under the P deficient conditions, the rate with which plants used P through roots also reduced due to the sorbed-P, which as such cannot be utilized (Nagarajah et al. 1968). The time-dependent P release from soils requires an understanding of mechanisms involved in the P reactions on soil colloidal complex (Singh and Singh 2016). The release and transport of PO_4^- ions from the manure applied soil has an unfavorable impact on the quality of surface water bodies due to P enrichment called 'eutrophication' (Jeremy and Daniel 2003). Under acidic conditions, inorganic orthophosphates ($H_2PO_4^-$ and HPO_4^{2-}) are the dominated P forms, which are absorbed by the plants (Mozaffari and Sims 1994).

After about 24 h of fertilizer-P application, almost ~80% of soluble-P is released into the soil solution, followed by the second phase of slow-release which continues up to 504 h (Jeremy and Daniel 2003). Total P released from the manure amended soils was ~29% in the top 10 cm soil layer, followed by ~8% from the sub-surface (45–65 cm) soil layer. The P release is rapid initially, followed by a slower release of 2160 h, and the Elovich equation was the best fitted kinetic model to determine the fate of P released into the soil solution (Yang et al. 2019). The amount of Pi (P_i-solubilized by oxalic and citric acids) increased with increasing organic acid concentrations. The oxalic acid exhibited a lower P_i solubility capability, compared with citric acid at a concentration of ≤ 1 m mol L^{-1}, whereas citric acid was higher at ≥ 1.5 m mol L^{-1}. Hosseinpur and Pashamokhtari (2008) reported that P release reached ~73% within the initial 15 days following bio-solid application in calcareous soil. Singh and Singh (2016) reported that cumulative P release was significantly ($p < 0.05$) higher after 12 weeks compared to that of 1 week after incubation. At aerobic and nearly saturated moisture regimes, non-calcareous soil had much higher cumulative P release compared to the calcareous soil. Phosphorus release from floodplain calcareous and non-calcareous soils proceeded in two phases. It increased rapidly with increasing equilibration time and gradually leveled off with shaking time enhancement. The Pi (at 25 mg kg^{-1}) and press mud (PM, 0.5%) application ($P_{25}PM_{0.5}$ and $P_{25}PM_{1.0}$) accelerated the P release from soils, and the reaction completed fast within 6–12 h of equilibration, indicating the dissolution of native P and conversion of non-labile to labile P pools. They compared nine different empirical models of varying complexity fitted to time-dependent P release data showed higher coefficient of determination for Elovich equation ($R^2 = 0.961–0.996^{**}$) followed closely by modified Crank's equation ($R^2 = 0.961–0.980^{**}$), power function equation ($R^2 = 0.946–0.995^{**}$) and differential rate equation ($R^2 = 0.903–0.997^{**}$).

The cumulative amount of P released in the inorganic fertilized plots was higher, and the rate of P release was much faster with fertilizer-P application than that of the biosolids amended soil (Derek et al. 2012). Parabolic diffusion equation best described the P release kinetics data, which showed that P desorption was mass-transfer limited process. The X-ray absorption trends near to edge structure revealed dissolution of Ca-P and Fe-P minerals occurs from the exchangeable sites. Under P deficient conditions or due to excessive P uptake, there is a rapid redistribution between the aqueous, adsorbed, and precipitated phosphate (PO_4^{3-}) species.

12.7 Mineral Solubility and Phosphorus Chemistry

Mostly mineral P forms of soils are found as insoluble forms viz. apatite, HA and oxy-apatite and Fe, Al, and Mn hydrated oxides (Grant et al. 2005). Phosphate reaction products are specific and specifically identifiable compounds, which are produced due to the application of fertilizer-P and its reaction with soil constituents. Phosphorus occurs in the soil in inorganic combinations, as it forms compounds with a variety of metals. Being chemically reactive, P exists in around 170 minerals (Halford 1997), however, organic forms constitute around ~15–80% of the total P in surface soils (Magid et al. 1996). Immediately after fertilizer-P application to soils, P undergoes fast transformations and changed into insoluble forms. During the start of the reaction, these are meta-stable and with time are converted to more stable P compounds. For the plants, meta-stable forms of P acts as a source for longer period of time (Black 1967). These reaction products primarily govern the availability of P to plants by controlling soil solution P concentration.

Bhujbal et al. (1986) recognized dicalcium phosphate (DCP) as a major reaction product after 2 weeks of incubation of ammonium nitro-phosphate fertilizer in vertisols, oxisols, alfisols, entisols, mollisols, and aridisols. Hasan and Bajaj (1982) reported the predominance of octacalcium phosphate (OCP) as a major reaction product of monocalcium phosphate (MCP) after 4 months of incubation in alluvial soils of Delhi. Black (1967) reported that in alkaline soils, OCP or apatite was the major reaction products, where monobasic calcium phosphate has been added. While studying the solubility and capacity relationship for residual available P in near-neutral and alkaline soils, Fixen and Ludwick (1982) reported that OCP was not likely an important residue in 27 out of 28 soils but TCP or a mineral similar to TCP in composition and solubility may have accompanied for at least a portion of fertilizer residue. Singh and Bahl (1993) in an experiment on ten soils varying in pH and $CaCO_3$ reported significant lowering of phosphate potential following combined application of 36 mg P kg^{-1} and *Sesbania*. Phosphorus solubility isotherms indicated an undersaturation with respect to OCP in most the neutral and alkaline soils. Sarkar et al.(1977) studied the reaction products formed in red soils of West Bengal following the application of MAP and MCP. They reported the formation of ammonium tarankite and variscite in soils of MAP application whereas reaction products of MCP caused the progressive dissolution of soil constituents and resulted in the formation of mainly colloidal amorphous Fe-Al phosphate compounds. While characterizing fertilizer-P reaction products in three texturally divergent soils, Ghosh et al. (1996) concluded that after 120 days of incubation followed by X-ray diffraction results in brushite, strengite, variscite as major soil fertilizer-P reaction products with ortho and polyphates as sources of P.

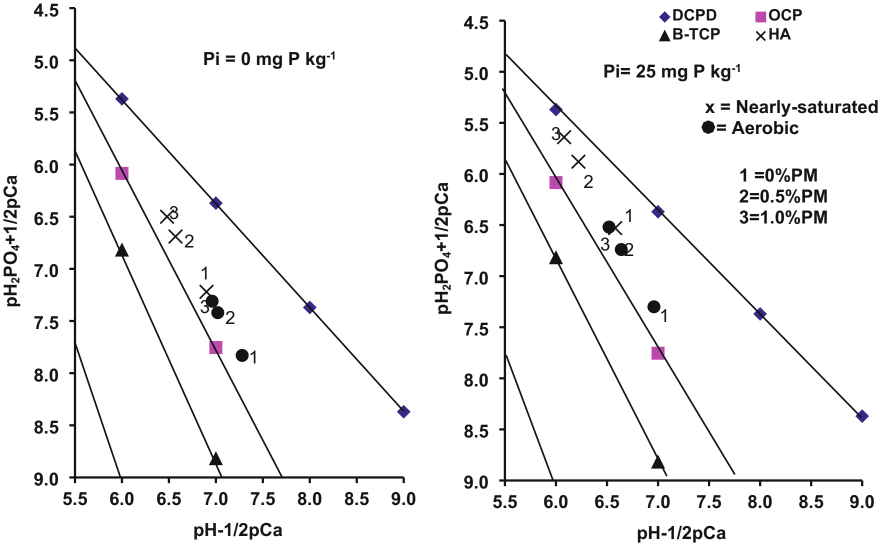

Fig. 12.3 Reaction products of P in sub-tropical calcareous soils (0—15 cm) without and with press mud (PM) and inorganic-P addition after 12 weeks of aerobic and nearly- saturated incubation (Source: Singh et al., 2010)

Integrated nutrient management as press mud (PM) and Pi application cause super-saturation with respect to dicalcium phosphate dihydrate (DCPD), delineating higher P availability in calcareous (Fig. 12.3) and non-calcareous soils (Fig. 12.4) (Singh et al. 2010). In the non-calcareous soils, solubility points shifted above DCPD, due to the lowering of phosphate potential, (Fig. 12.4). The standard phosphate requirement (SPR) was reported to decrease by 48.9 (45.0%) and 99.4 kg P_2O_5 ha^{-1} (90.9%), as quantity-intensity relationship because of PM application @ 0.5 and 1.0% under aerobic moisture regime, respectively in calcareous soil. A complete supplementation was, however, observed in non-calcareous soil in saturated soils where all the soil pores are water-filled and conducting it. Increased solubility of phosphatic compounds due to manure application has been related to decrease in phosphate potential (pH_2PO_4 + 1/2 pCa) of soils inculcated under soils at 60% water-filled pore space) and nearly saturated (90% water-filled pore space) moisture regimes (Table 12.4).

12.8 Artificial Intelligence for Predicting Soil P Availability

Modeling of nutrients availability in soils with contrasting physical and chemical properties and moisture regimes is important, which is normally used to develop relationships for variables. It has been effectively applied at different scales to

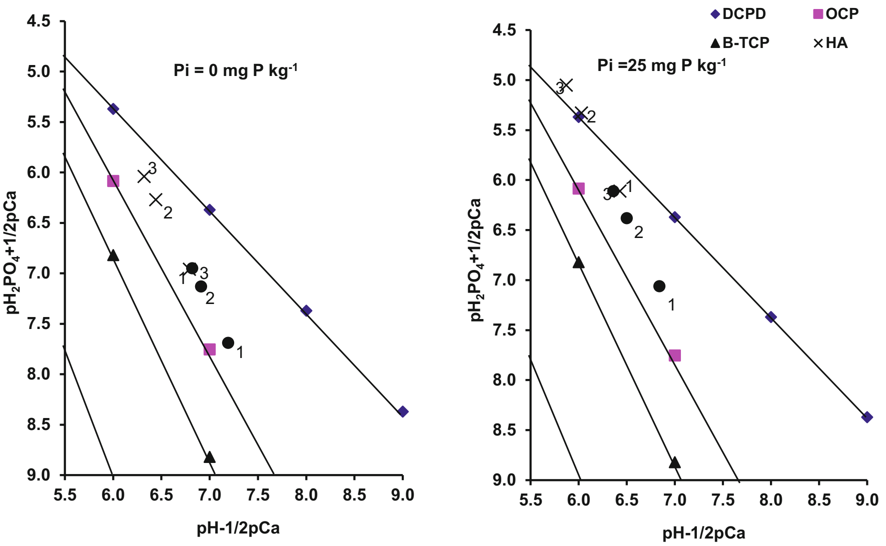

Fig. 12.4 Reaction products of P in sub-tropical non-calcareous soils (0—15 cm) without and with press mud (PM) and inorganic-P addition after 12 weeks of aerobic and nearly- saturated incubation (Source: Singh et al., 2010)

Table 12.4 Phosphate potential (pH_2PO_4 + 1/2pCa) of floodplain calcareous and non-calcareous soils amended with inorganic P and press mud incubated at aerobic (60% water-filled pore space) and nearly saturated (90% water-filled pore space) moisture regime (Source: Singh et al. 2010)

Inorganic P (mg kg^{-1})	No-Pressmud	Pressmud @ 0.5%	Pressmud @1.0%	Mean
	Calcareous soil, Aerobic (60% water-filled pore space) moisture regime			
0	7.83	7.42	7.31	7.52
25	7.30	6.74	6.52	6.85
	Non-calcareous soil, aerobic (60% water-filled pore space) moisture regime			
0	7.69	7.13	6.95	7.26
25	7.06	6.38	6.11	6.52
	Calcareous soil, nearly saturated (90% water-filled pore space) moisture regime			
0	7.22	6.69	6.50	6.80
25	6.53	5.58	5.64	6.02
	Non-calcareous soil, nearly saturated (90% water-filled pore space) moisture regime			
0	6.96	6.27	6.04	6.42
25	6.11	5.33	5.05	5.50

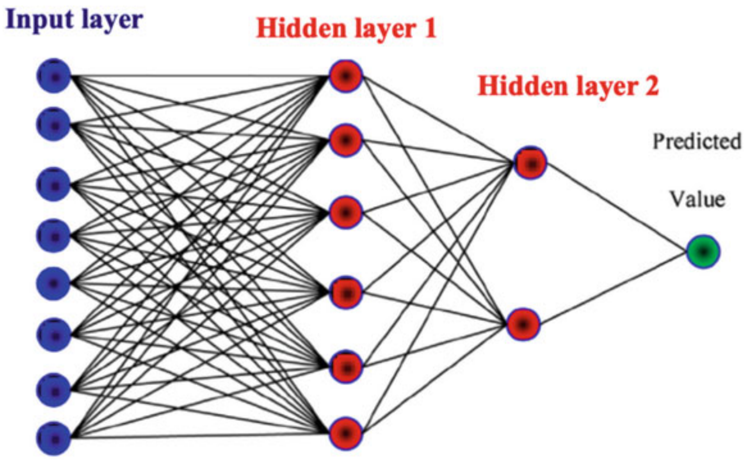

Fig. 12.5 The configuration of multi-layer artificial neural networks (ANN) for predicting variables

estimate soil physicochemical properties using attribute analysis (Omran 2012; Merdun et al. 2006). Soil P at field and landscape scales has been predicted from different related secondary variables using primary variables that can easily be obtained and be deduced from correlation and regression analysis with primary factors (McBratney et al. 2003). However, the efficiency of any model in predicting nutrient availability depends on several factors viz. complexity of land under consideration, digital elevation model (DEM) resolution, and input data quality (Wilson and Gallant 2000). These methodologies had the advantage of being cost-effective and time-saving in tedious soil analytical techniques, and often require a small sample size (McBratney et al. 2003; Sidhu and Kaur 2015; Sidhu and Kaur 2016; Kaur 2020). Over years, several statistical and multivariate techniques are developed for studying the relationships between spatially variable soil attributes across landscapes including geostatistical techniques, fuzzy logic, neural networks, linear and multiple regression techniques, etc. (Keshavarzi et al. 2015; Landeras et al. 2008; Kaur 2020). Artificial neural networks (ANN) are extensively used artificial intelligence tool used for predicting systems' performance particularly in the situations where the accuracy in prediction of highly complex systems are required, but limited field or laboratory experimental dataset is available (Najafi et al. 2009; Kaur 2020). A typical ANN consists of large numbers of highly interconnected processing units usually known as neurons (Thurston 2002; Singh and Kaur 2015; Sidhu and Kaur 2016; Kaur 2020). The ANN functions help to understand the non-linearity in datasets into neural networks that are more powerful compared with the linear transformation. Each ANN model is constituted by an input layer, sandwiched hidden layers, and lastly by outer layer (Fig. 12.5). The two elements of neural networks are the types of neural interconnection arrangement and algorithm type used to set the strength of relations. For modeling the complex

Table 12.5 Statistical measures for evaluating the performance of artificial neural network (ANN) used for predicting soil P (Source: Keshavarzi et al. 2015)

Topology	Training algorithm	Activation function	Epoch	Root mean square error (RMSE) (%)	Coefficient of determination (R^2)
3-6-1	Levenberg–Marquardt	Sigmoid	752	1.65	0.68

linkages between systems attributes, algorithms are mostly used which are capable of performing the assignment, without computing the explicit formulation of the relationships. The ANNs for delineating the input-output variables are not dependent on specific functions (Schaap and Bouten 1996; Singh and Kaur 2015; Sidhu and Kaur 2015; Sidhu and Kaur 2016).

Keshavarzi et al. (2015) used a neural network model for estimating soil P using terrain analysis by using the randomization technique and splitting of data sets into training and testing data. The finest structure of network was projected from coefficient of determination (R^2) and root mean square analysis (RMSE) values (Table 12.5). Their findings suggested that neural network model is highly affected by the slope and elevation, respectively that strongly influence soil P availability. The scatter plot for measured and simulated values for soil P showed that ANN model used for predicting P availability explained ~68% of the variation in the dataset.

For the estimation of soil P availability from easily measurable soil properties viz. soil organic C, clay content, $CaCO_{3,}$ and pH, Keshavarzi et al. (2016) used a new model, which could explain ~50% of the total variations in the datasets. By using support vector machine (SVM), multiple linear regressions (MLR), and ANNs, Li et al. (2014) revealed that through some important soil properties as independent variables, while soil nutrient content was taken as dependent variable for estimating the soil P status. They reported that SVM and general regression neural network (GRNN) models accuracy in judging soil nutrients were ~ 77.9 to 92.9%, respectively. Therefore, both the models viz. SVM and GRNN could be used for predicting the inherent nutrients levels in the fields which further helps for sustainable nutrient management. This helps in improving the resource as well as nutrient use efficiency for feeding the burgeoning population from declining land and water resources.

12.9 Conclusions

Phosphorus is one among the most yields limiting plant nutrients in the worlds' soil under crop production. It undergoes series of transformations immediately after its soil application, causing only a small fraction of it in available forms that tend to form an equilibrium with soil solution P concentration. Phosphorus chemistry in soils is highly dynamic and is often governed by soils' physicochemical properties. For better crop response of applied P, a pH range of 6.0 to 7.0 is considered important. The predominance of HPO_4^{2-} ions in a soil solution occurred between soil pH = 7.5–8.2 and preferential uptake of $H_2PO_4^-$ by plants, compared to HPO_4^{2-} which results in its reduced availability in alkaline soils. Among different clay types, 1:1 type clay (Kaolinite) has a higher P fixation capacity relative to 2:1 type clays (montmorillonite, illite, vermiculite, etc.). Phosphate sorption and release curves for silt and clay fractions revealed that clay fractions adsorbed 1 to 1.5 and 2 to 10-times higher P than silt fractions, respectively at the same equilibrium P concentration. About 90% variability in Po and Pi is related to soil texture with a negative correlation with the sand content of the soil. The presence of $CaCO_3$ (amorphous and crystalline forms) in the calcareous soils results in high P sorption reactions at reactive $CaCO_3$ surfaces due to increased Ca ion activity in the liquid phase. Conversely in the acidic soils, Al^{3+} and Fe^{3+} get attached to SOM and leads to the formation of metal-OM complexes causing P fixation. The integrated nutrient management (organic+ inorganic P) resulted in super-saturation with DCPD, delineating higher P availability in calcareous and non-calcareous soils. The non-calcareous soil pre-treated with manure and inorganic P under nearly saturated moisture regime exhibited a shift in the solubility points above DCPD, as a consequence of lowering of phosphate potential, indicating super-saturation with respect to DCPD. The SPR estimated from the Q/I relationships showed a significant decrease for calcareous as well as non-calcareous soils with integrated P management. Therefore, judicious and efficient P management is prerequisite for increased P availability and PUE, and food security of projected ~9 billion human populations by 2050. Estimates revealed that up to ~70% of the global P demand could be met through enhanced PUE, while the remaining demand could be met through a higher resurgence and P use from its sources.

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Role of Potassium for Improving Nutrient Use Efficiency in Agriculture

13

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Abstract

There is a growing need to improve the agronomic efficiency of plant nutrients, which has been declining over the years. Although the demand for nitrogen (N) fertilizers is increasing, there is a considerable reduction in yield increase per unit of N (nutrient use efficiency, NUE). Improving the NUE of N is of great importance, both for economic and environmental reasons. Insufficient applications of potassium (K), combined with excess N applications, is an increasingly serious problem for modern intensive agricultural systems. This often leads to great N losses, pollution of the environment, and low NUE. Recently, balanced nutrition –mainly N and K balanced nutrition and touching the subject of N and K synergistic effect–has been increasingly identified as an important strategy to improve NUE. Several studies demonstrate the positive effects of the interaction between N and K, particularly for crop productivity and economics, but balanced nutrition is not implemented correctly in various areas around the world. The application of K has been neglected in many developing countries, including India for example, resulting in soil K exhaustion and declining crop yields and quality. Optimal N: K nutritional ratios can reverse this trend by increasing yields and crop quality. Many long-term field trials have demonstrated how K application can also improve the NUE of phosphorus (P) and other nutrients like sulphur (S). Studies have also shown that K can mitigate the adverse effects of excessive N on disease and insect-pest incidences, thereby improving crop yields and health, thus, in turn, improving the NUE of N.

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Keywords

Potassium · Nutrient use efficiency · Balanced fertilization

Abbreviations

Al	Aluminum
Ca	Calcium
Cu	Copper
DM	Dry matter
Fe	Iron
K	Potassium
KUE	Potassium use efficiency
KSB	K solubilizing bacteria.
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
NR	Nitrate reductase
NUE	Nutrient use efficiency
P	Phosphorus

13.1 Introduction

Agriculture is currently under immense pressure to feed an increasing global population (Grzebisz et al. 2012). Not only does the sector face the serious challenge of growing enough healthy food to feed the expanding global population (FAO 2013), but this challenge is also deepening the constraint on global base resources (land, water, and air). Increasing yield per unit area is needed to help increase food production (Baligar and Fageria 2015). FAO (2013) estimates that about 1.54 billion ha of land globally is in use for cropping. The majority of land that is suitable for cropping is already being used, with the exception of some areas in sub-Saharan Africa and South America, but these areas are too brittle to cultivate due to soil degradation.

Soil degradation, caused by intensive cultivations and inappropriate management, combined with increased abiotic and biotic stress events poses a serious challenge to attaining reasonably good annual and perennial crop yields worldwide (Baligar and Fageria 2015). Sufficient nutrients supply (applied through fertilizers) together with superior genetic cultivars and genotypes, are essential to attain higher yields and high-quality food. Essential nutrient scarcity affects many of the world's soils, but high fertilizers application to reach higher crop yields might contain toxic elements as well (Dudal 1976; Clark 1982; Baligar et al. 2001). Various factors, including salinity, acidity, alkalinity, the nature of farming anthropogenic processes, and erosion, cause soil degradation and decrease soil fertility. About 4billion ha of the world's land suffers from soil acidity and about 950 million ha of land is salinized. To cultivate some of these areas requires costly inputs including irrigation, soil amendments, and fertilizers. Adding fertilizers to degraded and infertile soils is crucial for appropriate nutrient supply and attaining higher yields (Baligar and Fageria 2015). Nitrogen (N), phosphorus (P), and potassium (K) are the three main essential nutrients plants require in relatively large amounts for their metabolism and growth. A deficiency in any of these nutrients results in a significant reduction of crop yields (Mitra 2017). The reservoir of N, P, and K in cultivated soils is not sufficient to meet the needs of crops grown in the same area annually, so to reach optimum yields N, P, and K should be added every year through fertilizers.

World consumption of NPK fertilizers reached 186.67 million tons in 2016, up by 1.4% from2015. Between 2015 and 2020, the demand for N, P, and K fertilizers were estimated to have grown annually on average by 1.5, 2.2, and 2.4%, respectively. The global demand for fertilizer production, intermediates, and raw materials is also expected to increase (Roy et al. 2006). Chemical fertilizers are one of the more costly inputs farmers use to increase their yields. About12 million tons of N, two million tons of P, and four million tons of K are applied every year by farmers in North America (Baligar et al. 2001). About 18 million tons of N, 6.9 million tons of P_2O_5, and 2.5 million tons of K_2O were applied in India during 2018–2019 (FAI 2019). Global K_2O consumption since 1973 can be seen in Fig. 13.1. Despite fertilizer use increasing, plants being grown in many soils take up very little nutrients from applied inorganic fertilizers. Estimations of the overall efficiency of applied fertilizers have been about50% or lower for N, less than 10% for P, and about 40% for K (Baligar and Bennett 1986a, b). The efficiency of these nutrients under flood irrigated rice systems in Asia is even lower. Significant nutrient losses through leaching, runoff, gaseous emissions, and fixation by soil all contribute to low efficiencies. Nutrient losses may also contribute to soil and water quality degradation, ultimately leading to environmental degradation (Baligar et al. 2001). These reasons emphasize the need to improve nutrient use efficiency (NUE).

Blair (1993) defined NUE as the genotype's ability to uptake nutrients from a growth medium and to integrate or utilize them in shoot and root biomass production or functional plant materials such as seeds, grains, fruits, and forage. NUE usually is defined as the nutrient output or the crop output per unit of nutrient input (Meena et al. 2020; Naeem et al. 2017). Improved NUE of plants can reduce the rate of nutrient losses and fertilizer input costs and increase crop yields (Baligar et al. 2001). Various factors influence NUE: the plant's genetics, soil, fertilizers, agronomic management, biotic, and abiotic stresses. This chapter looks at the effect of K fertilization on NUE. Additional factors that can improve NUE can be seen in Fig. 13.2.

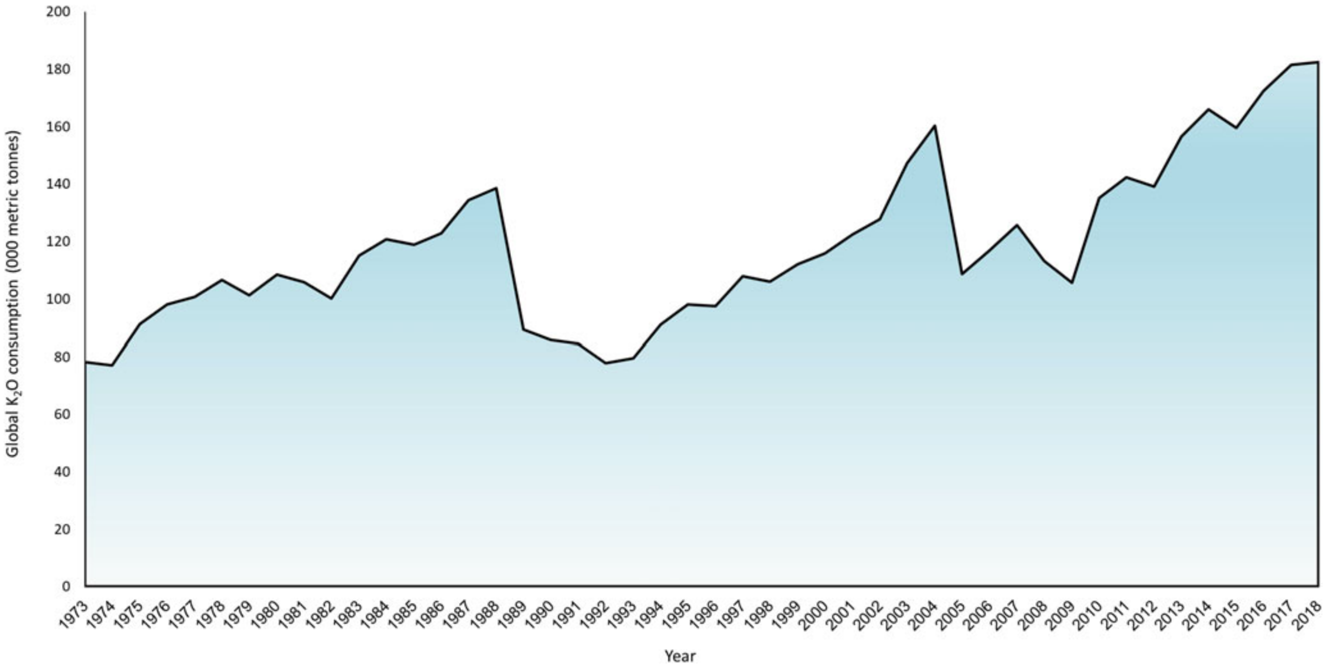


Fig. 13.1 Global K_2O fertilizer consumption, from 1972 to 2018 (adopted from IFA 2021)

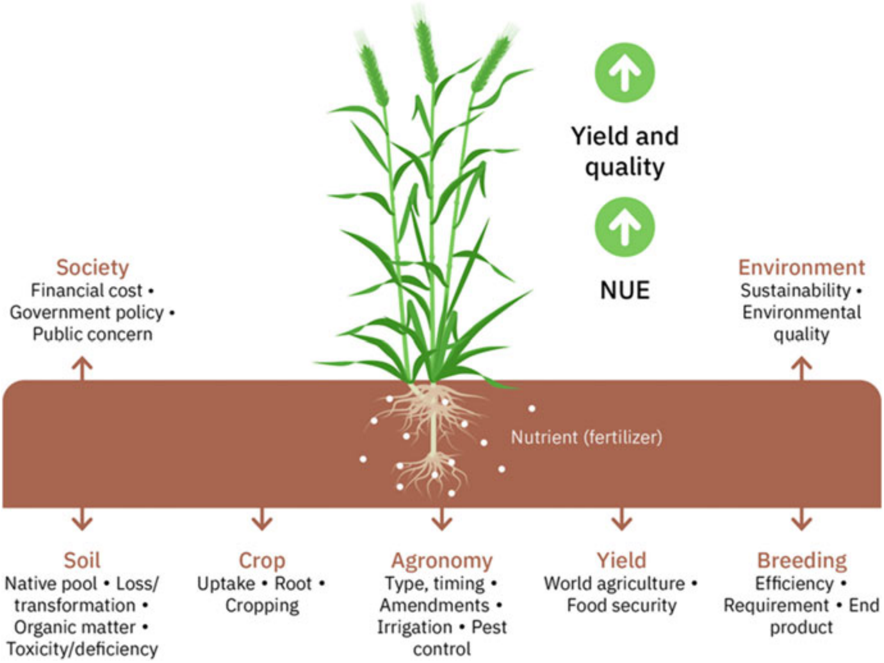


Fig. 13.2 Factors that can improve NUE, adopted from Mathur and Goel (2017)

13.1.1 The Role of K in Plants

K^+ is an essential mineral and the most plentiful cation in plants. K^+ is also unique as it occurs solely in the free ion form (Römheld and Kirkby 2010). In sufficiently supplied plants, K^+cancompose~6% of plant dry matter (DM) or in ~200 mM concentrations (Leigh and Wyn Jones 1984). The highest K^+ concentrations can be found in young developing tissues and reproductive organs, which can indicate its key role in growth and cell metabolism. K^+ activates several enzymes, some are involved in protein synthesis, energy metabolism, and solute transport (Mengel and Kirkby 2001; Amtmann et al. 2008). Other processes where $K^+$is found to be involved include stomatal movement, osmoregulation, and cell extension, phloem loading, photosynthesis, and transport and uptake (Römheld and Kirkby 2010). K^+ is needed by plant cells to maintain transmembrane voltage potential for homeostasis of cytoplasmic pH and transporting inorganic anions and metabolites (White and Karley 2010). K^+ is the main cation in long-distance transport inside the xylem and phloem, participating in neutralizing anions, giving its high mobility through the whole plant (Jeschke et al. 1997). K^+ up-taking and accumulating by plant cells is the main driving force for cells' osmotic expansion (Uchida 2000; Mengel and Kirkby 2001).

The most common symptom of K^+ deficiency is chlorosis along leaf edges, which is also known as leaf margin scorching (Fig. 13.3). Chlorosis occurs first in older

Fig. 13.3 Potassium deficiency in soybean (IPI website)

leaves, due to the high rate of K^+ allocation from mature to developing tissues. First, the growth rate decreases (known as hidden hunger), and then later chlorosis and necrosis appear in the older leaves. Because K^+ is required in photosynthesis and protein synthesis, K^+ deficient plants will have slow and stunted growth. In some crops, stems become weak, and lodging incidences increase. The size and production quantity of seeds and fruits size and their production quantity are also reduced. Plants with K^+ deficiency demonstrate turgor decrease and become flaccid under water stress, especially during the middle of the day (Uchida 2000; Mengel and Kirkby 2001). K^+ also contributes to plants survival under various abiotic stresses (Wang et al. 2013), as well as environmental stress conditions and many physiological processes. These include protein synthesis, energy transfer, enzyme activation, photosynthesis and translocation of photosynthates into sink organs, osmoregulation, stomatal movement, phloem transport, cation–anion balance, and stress resistance, and decreasing excess uptake of ions like sodium (Na) and iron (Fe) in flooded and saline soils (Mengel and Kirkby 2001; Marschner 2011).

13.1.2 Potassium Uptake by Plants

K content in soils ranges between 0.5–2.5% and about 2–10%of a plant's dry weight is made up of K (Gierth and Mäser 2007). K is highly important for plants, as shown by the sophisticated mechanisms of K uptake, redistribution, and homeostasis, and is a component in numerous cell wall and membrane protein families (Hirsch et al. 1998; Armengaud et al. 2004; Szczerba et al. 2009; Pyo et al. 2010). Numerous regulatory mechanisms have been identified for K transporters. These transporters are activated by different environmental factors, including K^+, Na^+, and Ca^{2+-} concentrations in the soil and water availability. Many proteins in the plant are involved in K^+ transportation (Mitra 2017).

There are two K transport systems: (1) a low-affinity transport system, which is channel-mediated that acts when external K concentrations are high and is iso-thermodynamically passive (Leigh 2001; Szczerba et al. 2009) and, (2) a high-affinity transport system, a system that can reach saturation, which accelerates the thermodynamically active K uptake when external K concentrations are low ($<$ 1 mm) (Schachtman and Schroeder 1994; Szczerba et al. 2009; Cuéllar et al. 2010). The capacity of a plant to uptake K and maintain internal homeostatic properties is ruled by genetic expression mechanisms (Hirsch et al. 1998; Yin et al. 2011; El-Mesbahi et al. 2012). Furthermore, K uptake is closely associated with water budget (Sardans and Peñuelas 2015). K and water transmembrane channels are probably co-regulated and their function is synchronized to maintain proper cytosolic osmolarity (Patrick et al. 2001; Liu et al. 2006; Osakabe et al. 2013).

13.1.3 Potassium Use Efficiency (KUE)

Information about KUE is inadequate compared with N and P (Mathur and Goel 2017). K^+ is one of the most abundant minerals in the earth's crust. The lithosphere contains approximately 2.5% of K^+.K soil concentrations for mineral soils differs broadly, between0.04 and 3.0% (Sparks 1987). Various rocks are a source for K, including igneous rocks like granites and syenites (46–54 g K kg^{-1}), basalts (7 g K kg^{-1}), and periodotites (2 g K kg^{-1}), sedimentary rocks such as clayey shales (30 g K kg^{-1}), and limestone (6 g K kg^{-1}) (Malavolta 1985). Even though plants can uptake K^+ from the soil solution, most K^+ in soil is unavailable as it is fixed and in lattice forms (Syers 1998; Ashley et al. 2006). Soil K (Fig. 13.4) can be divided into four categories: (1) K in the soil solution (2) exchangeable K, (3) non-exchangeable-K, and (4) structural K (Syers 2003; Moody and Bell 2006). Exchangeable K can be released rapidly from soil particles to enter the soil solution, but K release from the other three forms is much slower and so will not be as readily available. The portion of available K in soil solution is 0.1–0.2% of total soil K, exchangeable K is 1–2%, non-exchangeable K is 1–2% (fixed in 2:1 clays), and soil-unavailable K is 96–99% (Sparks 1987; Wang et al. 2010; Britzke et al. 2012; Sardans and Peñuelas 2015).

On top of the issue of restricted K^+ availability, other soil components also interfere with K^+ uptake, e.g. high concentrations of NH^{4+} and Na^+ disturb plant roots K^+ uptake (Qi and Spalding 2004; Ashley et al. 2006). K availability differs with soil types and is largely affected by the soil's physical (type and amount of clay and organic matter), biological, and chemical properties. Soil K is also influenced by the parent material's nature, weathering degree, the addition of manures and fertilizers, leaching, erosion, and crop removal (Dhillon et al. 2019). Another factor influencing the efficiency of K^+ uptake in plants is soil moisture (Shin 2014; Meena et al. 2020).

There are a couple of mechanisms that enable plants to adjust and survive limited K^+ conditions. As soon as plants sense a shortage of K^+, root volume is increased, which enables increased K^+ to uptake from the soil, and the high-affinity K^+ uptake system is activated. When plants cannot adjust and raise K^+ uptake and available K^+

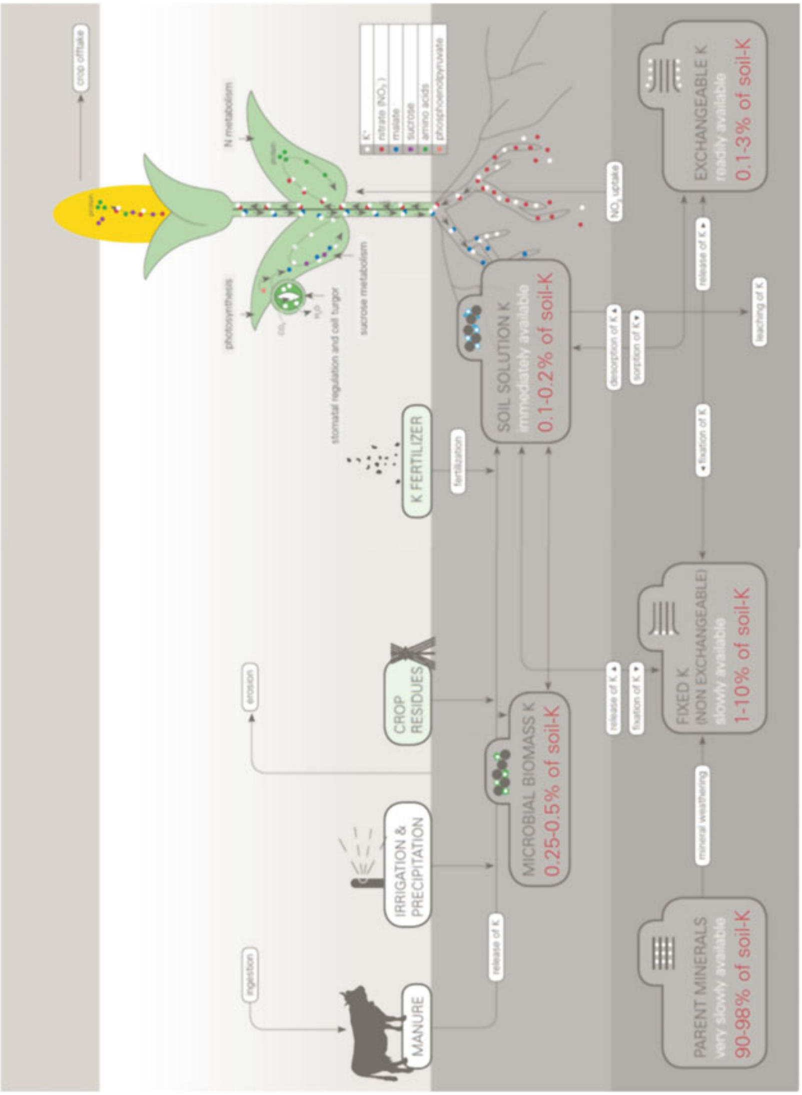


Fig. 13.4 The potassium cycle in soil (IPI website)

relocation internally, their metabolism rate decreases, and ultimately the plant stops growing. In agricultural crops, K^+ limitation results in reduced yields, but one solution is to either increase fertilizers usage or improve the efficiency of K^+ uptake, transport, and utilization (Shin 2014). Calculating KUE is based on the relationship between the amount of fertilizer consumed by a certain crop and the amount of K removed by the plant. To determine global KUE for crops, the following equation (adapted from Raun and Johnson 1999; Dhillon et al. 2017) can be used:

$$\mathrm{KUE} = \frac{\text{Crop yield}\,K\,\text{update} - K\,\text{removed from soil}}{K\ \text{applied as fertilizer to the crop}} \times 100 \tag{13.1}$$

13.1.4 Nutrient Use Efficiency Estimation in Plants

A plant NUE is greatly affected by its physiological and genetic makeup, which impacts a plant's capability to uptake and employ nutrients under several environmental conditions. To determine NUE, it can be beneficial to distinguish plant species genotypes and cultivars by their nutrient uptake and assimilation abilities for maximizing DM production and yields. Three efficiency mechanisms determine NUE:

1. Uptake efficiency: which is affected by absorption from the soil, influx kinetics and influx rate into the roots, radial transport (based on root parameters per length or weight). Uptake is correlated as well to particular amounts of nutrients that are already present in the soil or were applied.
2. Incorporation efficiency: refers to nutrient transport to the plant upper organs, based on shoot parameters.
3. Utilization efficiency: which is based on remobilization and whole plant parameters.

Plant NUE can be characterized as the maximum economic yield, or DM produced per unit of an applied nutrient or a unit of that nutrient that was taken up (Baligar and Fageria 2015). Figure 13.5 presents the different yield responses to nutrient levels.

13.2 Potassium for Improving Nutrient Use Efficiency

The average amount of available K in most soils globally is not sufficient to meet the nutritional needs of sensitive and high-yield crops (Gaj and Górski 2014). Intensive cropping, combined with unbalanced fertilization, causes K depletion in soils (Igras and Kopiński 2009). K deficiency, particularly in crop production, is usually caused by increasing applications of N and P fertilizer while neglecting K fertilization (Ju et al. 2005). K deficiency is a problem globally (Dobermann et al. 1998), and

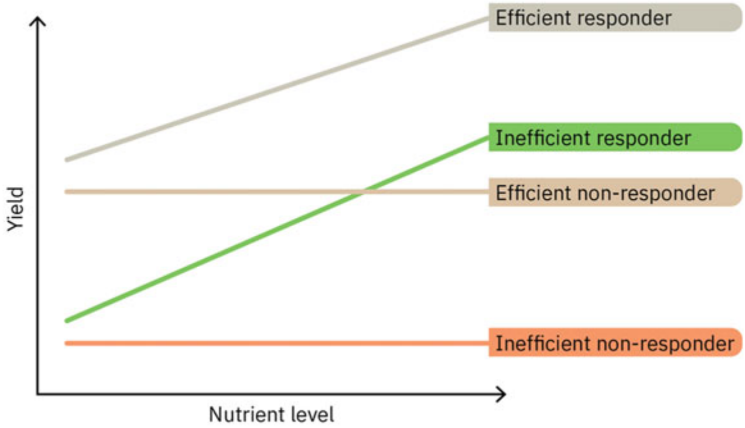


Fig. 13.5 Plant classes, relative to yield responses and nutrient level in the growth medium (adopted from Gerloff 1987; Blair 1993)

levels of K are decreasing in cultivated soils in Africa, Asia, Europe, and North America (Tan et al. 2012). Unbalanced K and P fertilization is a common cause for low N utilization, due to competition on absorption sites for example (Gaj and Rębarz 2014; Yadav et al. 2020). The efficiency of fertilizer use is also low as a result of current global N management strategies for crop productions systems (Cassman et al. 2002; Fageria and Baligar 2005), where N is often being applied in excess on the count of other nutrients. The relationship between nutrient uptake and yield is reflected as NUE and is expressed through economic products, such as grains (van Duivenbooden et al. 1996). To maximize NUE from mineral fertilizers, an analysis of the amount of nutrient applied, and its uptake is required, in addition to determining the factors limiting nutrient use (Gaj and Rębarz 2014).

In crops, nutrient interactions happen when one nutrient supply affects the absorption and employment of other nutrients. This occurs when one nutrient is in excess concentrations in the substrate (Fageria et al. 1997). Nutrient interactions happen at the root surface and inside the plant and can be divided into two main categories:

1. Interactions between ions when they are capable of forming a chemical bond. In this class, interactions are due to precipitates or complex formation. For instance, this interaction type happens when liming acid soils reduce the concentration of the majority of micronutrients (Fageria 2001), by reducing the soil pH and their availability to plants.
2. Interactions between ions with chemical properties are similar enough that they compete for transport, adsorption sites, and function on the root's surface or inside plant tissues. These kinds of interactions are more likely to occur between nutrients with a similar charge, size, coordination geometry, and electronic

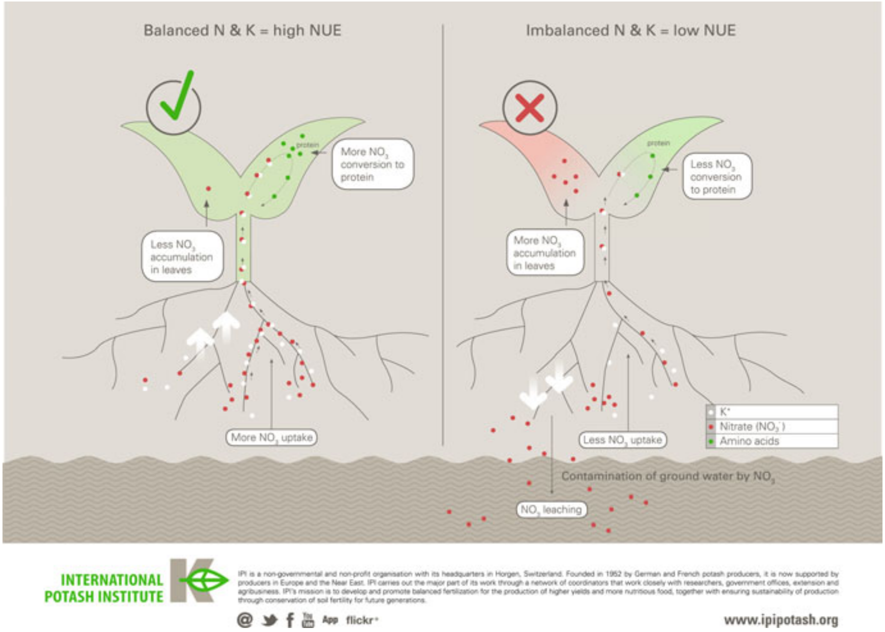
configuration (Robson and Pitman 1983). This is common for Ca^{2+}, Mg^{2+}, K^+, and Na^+, for example.

13.2.1 Potassium and Nitrogen Use Efficiency

Interactions between K and N have been well documented, with the first experiments starting in 1852 at Rothamsted Station, UK (Ranade-Malvi 2011). Some of the interactions that affect crop response to a nutrient like K are due to factors such as fertilizer form, method, and date of application, and the variety of crops. Occurrence of such K and N interactions may lead to changes in the ways of using K fertilizers (e.g. changing N:K ration when fertilizing). The most important variables are qualitative, such as the level of other nutrients applied, irrigation rate, spacing between plants, etc.

The interaction of K with other nutrients, particularly with N, is the most important variable (Loue 1980). K application, for example, could improve N metabolism enzyme activity (Hu et al. 2016; Zahoor et al. 2017). N and K interactions are important for crop production. The importance of N-K interactions and how best to manage this is increasing due to demand for higher crop yields globally, increasing cropping intensity, and considerable K depletion in cultivated soils (Aulakh and Malhi 2005). Crops with high K requirements often show strong N-K interactions (Loue 1980; Singh 1992). Plants uptake N either in a cationic (NH_4^+) or anionic (NO_3^-) form. This creates unique anion–cation and cation–cation interactions with K. The majority of current research findings have revealed that Kdoesnotcompete with $NH_4^+$for uptake but increases NH_4^+assimilation in the plants and prevents possible NH_4^+ toxicity (Aulakh and Malhi 2005). Mengel et al. (1976) determined that it is improbable for K to compete with NH_4^+ for selective binding sites during the uptake process. The relationship of K and N use efficiency, and its effect on yield, is shown in Fig. 13.6 and Table 13.1.

Ranade-Malvi (2011) was observed that crop response to N fertilizer applications was reduced when exchangeable K content in the soil was below optimal levels. Mengel et al. (1976) reported that while a higher K supply caused a decrease inNa^+, $Mg^{2+,}$ and Ca^{2+}uptakeby the shoots, NH_4^+uptake was increased. Mengel et al. (1976) reported that higher K concentrations in the solution were favoring the labeled N translocation from roots to shoots. In certain cases, higher K levels also enhanced the labeled N transfer rate from the soluble to the insoluble N fraction. On the other hand, increasing Mg^{2+} levels in the uptake solution had no effect on the uptake of labeled NH_4^+. Steineck (1974) revealed (through his nutrient solution technique) that there is a close relationship between N and K in their physiological functions and the main effect of KisimprovingNutilizationefficiency. Increased K uptake led to increased N uptake and vice versa: plants take up the amount of K required for full N utilization (Steineck 1974). The effects of both nutrients on plant composition and yield have an important impact on the nutrient cycle, especially when crops with high K uptake (like forage crops) are concerned (Loue 1980). Figure 13.7 provides an example of potato response to increasing K concentrations.



IPI is a non-governmental and non-profit organisation with its headquarters in Horgen, Switzerland. Founded in 1952 by German and French potash producers, it is now supported by producers in Europe and the Near East. IPI carries out the major part of its work through a network of coordinators that work closely with researchers, government offices, extension and agribusiness. IPI's mission is to develop and promote balanced fertilization for the production of higher yields and more nutritious food, together with ensuring sustainability of production through conservation of soil fertility for future generations.

Fig. 13.6 Potassium and nitrogen use efficiency (IPI)

Table 13.1 Increase in yield and NUE achieved in IPI on-farm experiments. Adopted from *e-ifc* No. 13, 9/2007. IPI

Crop	Country	Parameter	N rates (kg/ha)	K rates (kg/ha)	Yield increase (kg/ha)	NUE increase (%)
Maize	India	Grain	125	30–90	200–1300	6–29
Maize	China	Grain	150–300	75–180	200–1800	5–29
Maize	Ukraine	Grain	30	30	720	15.5
Rice	Bangladesh	Grain	100	33–66	690–900	23–30
Rape seed	China	Seeds	180	113–188	142–704	35–53
Sugarcane	India	Cane	240–340	85–200	2200	70
Sunflower	Hungary	Seeds	80	100–200	200–1100	10–30
Sunflower	India	Seeds	60	30–690	400	18
Wheat	China	Grain	180–300	75–150	200–1370	2–26
Winter rye	Belarus	Grain	90	60–120	230–610	10–23

Ajayi et al. (1970) reported that when tomato plants were given a continuous supply of N in the form of NH_4^+, severe stem injuries were observed unless K^+ was added at equivalent rates. Leaf injuries were seen to be a result of NH_3 toxicity when plants were treated with NH_4^+, but when plants received higher K rates, the injuries

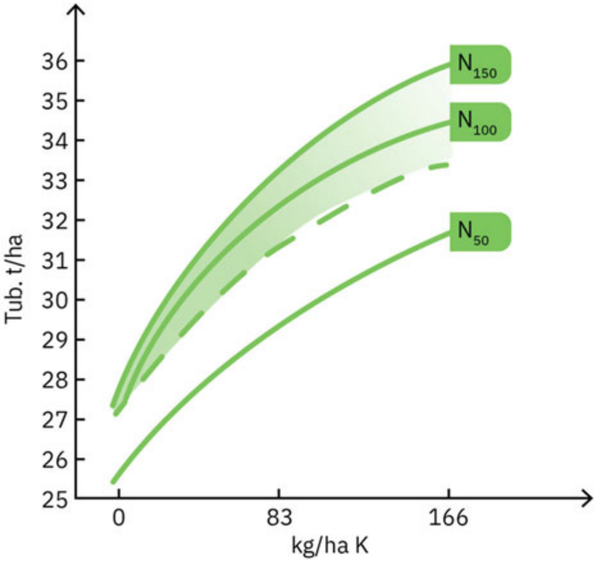


Fig. 13.7 Response to increasing K at 50, 100, and 150 kg/ha N in potato crops. The shaded area shows how the response to N increases as the K level is raised (mean of 17 years) (adopted from Loue 1980)

did not appear. Their conclusion was that K^+ boosted NH_4^+assimilation in the plant, which avoided NH_3 toxicity, and that K^+ uptake did not compete with NH_4^+uptake. Similar phenomena were observed in corn plants, where injuries appeared when $NH_4^+$and NO_3^- were applied at low K^+ concentrations (Dibb and Welch 1976). Based on their work on rice, Mengel et al. (1976) also concluded that it was improbable that K^+ competed with $NH_4^+$for selective binding sites in their uptake process. In fact, increased N and K uptake, combined with higher K rates, indicates a possible complementary uptake effect amid NH_4^+ and K^+ (Dibb and Thompson 1985).

Translating a plant's genetic code to produce proteins and enzymes is impossible without adequate K. Although N is fundamental for producing proteins, K-deficient plants will not produce proteins even with high levels of available N. This is because the enzyme nitrate reductase (NR) which catalyzes protein formation is influenced by K (Ranade-Malvi 2011). K does not activate NR but was found to be the most effective monovalent cation in its synthesis (Nitso and Evans 1969). In maize, NR activity was enhanced with increased K, therefore, it is likely that K ions influence NR synthesis (Khanna-Chopra et al. 1980). Starchsynthetase was also found to be affected by K. Nitso and Evans (1969) found that K is needed for starch synthetase in sweetcorn. Starch synthetase showed optimum activity in the presence of 0.05–0.1 M of K, while other monovalent cations were not so efficient. Lower amounts of starch mean that less starch is moving from source to sink, leading to a poor-quality end product. One practical implication of the N-K interaction is that applications of large amounts of N when there is insufficient exchangeable K in the soil are not beneficial. That is because N is not used efficiently and is expressed as a financial cost to the grower (Ranade-Malvi 2011).

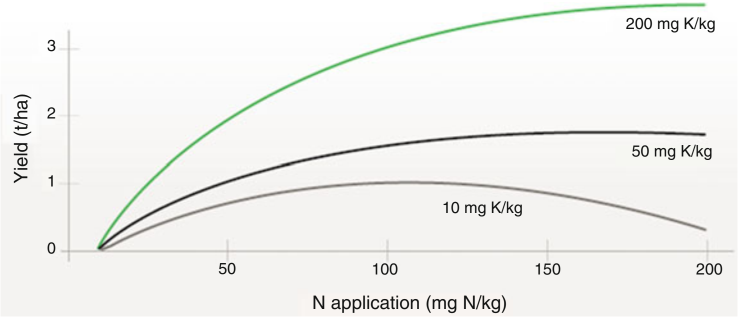


Fig. 13.8 Effect of N and K interaction on barley yield in hydroponic culture, adapted from (Macleod 1969)

One of the main reasons for a low potato yield is the low efficiency of applied N fertilizer (Singh and Lal 2012; Grzebisz et al. 2017). Current mineral nutrition management in potato production is N-oriented and overlooks other minerals like K and P. Consequently, harvested yields are very variable year-to-year (Grzebisz et al. 2010). Increasing K levels above current recommendation levels improve N use efficiency in potatoes, which also allows N application to be reduced below recommended levels and increase tuber yields (Grzebisz et al. 2017). Trials in pigeon pea (*Cajanuscajan L. Millsp.*) showed that P and K application significantly increased grain and protein yield (Brar and Imas 2014). Increasing K level has been shown to not only increase grain yield but also improve N use efficiency by 6–29% in maize, 18% in sunflower, and up to 70% in sugarcane (IPI 2007).

Macleod (1969) reported that a plant's response to N was dependent on both P and K, increasing K levels improved barley responses to N fertilization, meaning that with high K levels less N can be applied to obtain a high yield (Fig. 13.8). Mondal (1982) identified a positive N-K interaction in rice. A low increase in yields was recorded when N levels were high and K applications levels were low, but yields increased with higher K application levels, meaning that there is a better utilization of applied N when N and K application levels are balanced. Muthuswamy and Chiranjivi (1980) reported that in Tamil Nadu (India), the optimal rate for fertilizer application for cassava was found to be 50 kg N/ha and 250 kg K_2O/ha. The N-K interaction resulted in very low yields when N was applied without K applications. The yield increased remarkably with increased levels of applied K. K application ensured N utilization and carbohydrate storage in cassava roots, thus improving N use efficiency. The impact of KUE on N use efficiency can be seen in Fig. 13.9.

Duan and Shi (2014) reported that adding K to N and NP fertilizers resulted in significantly higher N use efficiency both in rice and wheat. They concluded that there is a great potential for improving N use efficiency in China by adding K to NP fertilization. Hou et al. (2019) revealed that N and K combined applications increased rice grain yields by 42.2%, 62.9%, and 39.0% compared with treatments without NK fertilizers over 3 years. A suitable N and K combination improved grain yields and reduced the rates of N applications. Dong et al. (2010) also demonstrated

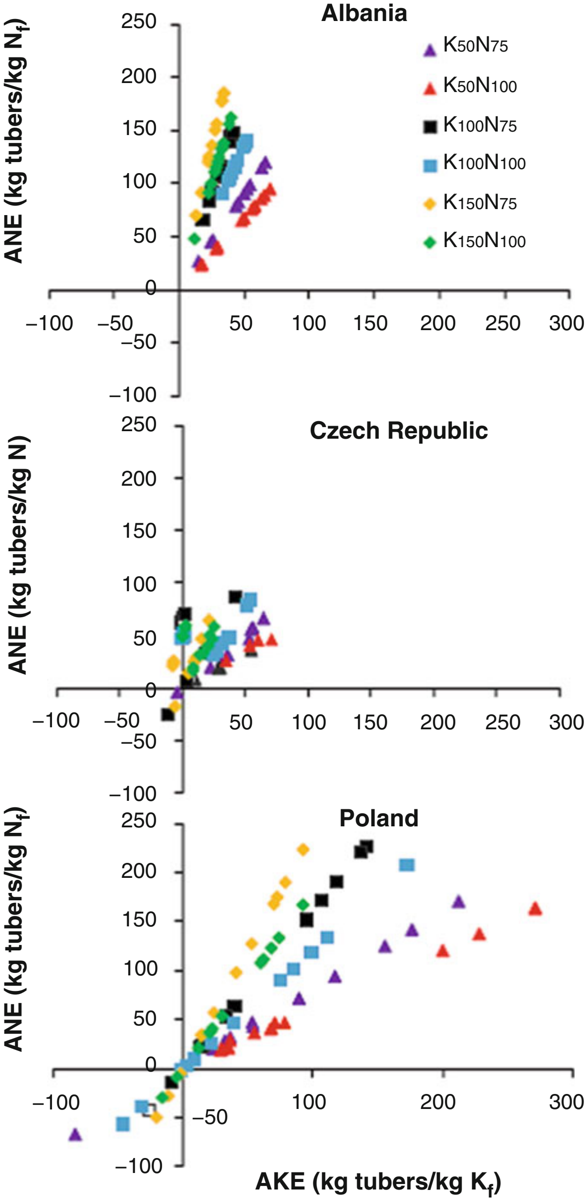


Fig. 13.9 Impact of the apparent potassium efficiency (AKE) on the apparent nitrogen efficiency (ANE) at six different N combinations (75% and 100% of the recommended rate) and K (50, 100, and 150% of the recommended rate) application levels (Grzebisz et al. 2017)

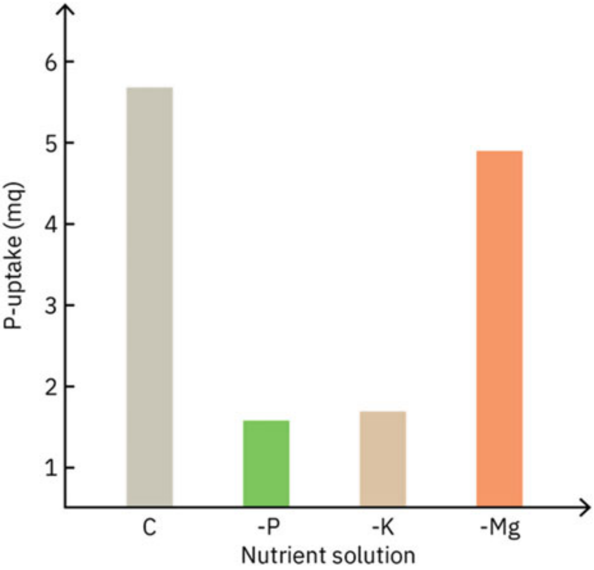
that N inputs can be reduced when combined with K without causing yield reduction. N supply with growing K rates increased grain yields and promoted the uptake of N and K. Other research has shown that the response of grain yields to N applications was higher with higher K rates than lower K rates: 120 and 180 kg K_2O ha^{-1} vs. 0 and 60 kg K_2O ha^{-1} (Hou et al. 2019). K has been found to promote higher root growth in rice, and to activate plant enzymes involved in assimilating ammonium and amino acid transport, causing increased N uptake and hence improved N use efficiency (Li et al. 2012). Improved N use efficiency contributes to farmer's profitability and can also decrease undesirable environmental effects (Jing et al. 2007).

13.2.2 Potassium and Other Nutrient's Use Efficiency

P is regularly applied to meet a crop's nutritional needs since sub-optimal P application can cause yield losses of 10–15% compared with maximum yields (Shenoy and Kalagudi 2005). Enriching soils with P do come with the risk of polluting surrounding water systems, which has become a growing environmental concern (Liu et al. 2011). Recovery of P by plants, through applied fertilizers, has been shown to be low—about 10% (Johnston 2000; Shenoy and Kalagudi 2005). Consequently, most applied P stays in the soil and is prone to be lost during the post-harvest season. Losses of P are affected by the application rates of P fertilizers and by the uptake of P by plants (Leinweber et al. 1999). Generally, the long-term build-up of soil P through the addition of levels of P higher than crop demand increases the risk of P losses (Liu et al. 2011). P-K interactions have less impact than N-K interactions and have attracted less attention. It appears that there is no close connection between the functions of P and K in plant nutrition. While N and K are taken up by plants in large amounts, P uptake is relatively small. It seems that P-K interactions are only noticeable when soils are supplied with insufficient P and K (Loue 1980). P movement in the soil and plant P uptake is usually associated with water content (Liu et al. 2011). Nevertheless, P and K are vital for enzyme and energy-driven reactions, photosynthesis, stress tolerance, seed formation, and quality, and crop maturity.

Robertson et al. (1954) reported that the effect of P on increasing vegetative growth in maize was significantly lower when P was applied as a starter fertilizer without N and K, compared with when P was applied with N and K. Applications of P only led to increasing grain yields when K and N were also applied. Fageria et al. (1990) found that fertilization with K significantly affected N, P, and K concentrations in the plant tops in lowland rice cultivars. K application both increased N concentrations in rice cultivars and increased P concentrations in plant tissues. Khanghahi et al. (2018) found that inoculating rice with K solubilizing bacteria (KSB), not only increased grains and straw K uptake but also improved N and P concentrations in the grain and straw, particularly when they were combined with half K chemical fertilizer (47.5 Kg/ha) application. Adequate K levels have been found to be necessary to achieve maximum crop response to added P. Wagner (1979) stressed the importance of P-K interactions in maximum yield production. Jones et al. (1977) reported on the need for balanced P-K application to achieve high soybean yields. Welch et al. (1981) showed a similar positive P-K interaction on bermudagrass yield. Adepetu and Akapa (1977) discovered a potential P-K interaction in the uptake stage. They proposed that since K^+ deficiency caused a significant

Fig. 13.10 Effects of potassium and magnesium on root potassium uptake of HI 13–4 cowpea grown in a nutrient solution (adopted from Adepetu and Akapa 1977)



reduction in P uptake, even with sufficient P levels in the solution, K^+ activates a specific P ion absorption site, and adding Mg^{2+} to the solution did not activate the P absorption site (Fig. 13.10).

Magnesium (Mg) and Calcium (Ca) usually have a negative correlation when applied with K concentrations, probably due to competition for absorbing sites (Loue 1980). Nevertheless, it seems that the negative effect of K on Mg uptake is concentration depended. Fageria (1983) reported that Mg uptake increased with increasing K concentrations up to 511 μM, but when K concentrations further increased a decrease in Mg uptake was observed. This depressing effect of K on Mg uptake at higher concentrations may be as a result of competition for metabolically produced binding compounds (Omar and Kobbia 1966).

A physiological relationship was found to exist between iron (Fe^{2+}), $K^+$and organic N in sorghum grains (Matocha and Thomas 1969). Soil and foliar Fe applications increased grain yields and were linked to amplified tissue K^+ concentrations. K applications without Fe^{2+}reduced yields, while the uppermost yields were reached with Fe^{2+} and K^+ applied together. Added K^+ was reported to reduce mild Fe^{2+} deficiency symptoms in potatoes (Bolle-Jones 1955). The effect of K^+ on Fe^{2+} toxicity in rice was evaluated. Roots of K^+ deficient plants decreased Fe^{2+} excluding power; therefore, Fe^{2+} toxicity is increased. Plant roots which received sufficient K^+had more metabolic activity in the roots and a higher rate of Fe^{2+} excluding, consequently reducing Fe^{2+} toxicity (Tanaka and Tadano 1972).

Synergetic effects of K and manganese (Mn) interaction have been reported in several studies (Stukenholtz et al. 1966; Smith 1975; Leggett et al. 1977). P, Ca, and Mg has a key role in Mn absorption regulation by plants (Ramani and Kannan

1974). P, Ca, and Mg was shown to decrease Mn uptake when Mn concentrations were in large and potentially toxic amounts. On the other hand, they elevated Mn absorption when its concentration was low. K has been found to increase Mn concentration in alfalfa but had no effect on Fe or aluminum (Al) accumulation (Smith 1975). An increase in Mn content was detected in burley tobacco leaf when K applications were increased (Leggett et al. 1977). When high levels of P and k were applied, total Mn accumulation was nearly tripled in corn plants (Stukenholtz et al. 1966). K application also caused an increase in copper (Cu) content in bent-grass (Waddington et al. 1971), and amplified K and Cu concentrations in blue-joint grass but only when P was present (Laughlin 1969). Responses to additional K applications have included higher forage yield and DM production, accompanied by higher Cu concentrations.

13.3 Conclusions

The need to improve fertilizer use efficiently (to achieve a higher NUE), especially when it comes to N fertilizers, is greater than ever before. The constant increasing demand for food is resulting in greater N fertilizer usage, yet this is having a negative impact on the environment. Balanced fertilization can reduces excess N usage, which results in N cascading into the environment. For example: without sufficient K levels, NO_3willaccumulate in the roots, then further NO_3 uptake will be stopped by a feedback mechanism in the root cells. As a result, NO_3stays in the soil and can be lost to the atmosphere as N gas or nitrous oxide, a greenhouse gas. Adequate supply of K not only increases yields but also increased N concentrations in the crop, resulting in smaller quantities of NO_3 left in the soil at harvest. When residual N is lower, contamination groundwater potential risk is decreased. Sufficient K soil reserves are therefore crucial for achieving an optimal response to N and increasing maximum N use efficiency. Where K reserves have been exhausted due to lack of K applications, applying larger Namounts is not economically viable and will leave a large amount of nitrate that risks being lost by leaching, and damaging the environment.

To conclude, improving NUE by supplying enough K can be beneficial in several aspects:

- Fertilizer dose reduction (especially N) is more economical for farmers.
- Obtain higher yield potentials due to synergistic nutrient interactions.
- Increase plant tolerance to damage caused by pests and diseases and possibly increase resilience to drought.
- Positively influence crop quality and biochemical components of the final product, e.g. proteins, oil, fatty acids, etc.
- Reduce the amount of residual nutrients left in the soil after harvest, consequently reducing the potential for environmental damage caused by leaching and emissions of greenhouse gases.

Further research should be carried out on genetic improvements (breeding, genetic engineering) to improve crop NUE, estimating crop K requirements based on location and crops physiology, and using modern tools to study K interactions with other nutrients.

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Integrated Approaches for Biofortification of Food Crops by Improving Input Use Efficiency

14

Hari Ram, Maninder Kaur, Neha Gupta, and Balwinder Kumar

Abstract

About 33% of the human population is facing micronutrients deficiencies like zinc, iron, iodine, and selenium which have become serious health problems across the globe especially in the developing nations including Asian and African countries. The hidden hunger reduces the gross domestic product of the developing world up to 5 per cent. So the adequate intake of these micro/trace elements is required for normal human health. Supplemental intake through injections, tablets, and supplements although are effective but are not economical. So bio-fortifying cereal grain crops with zinc, iron, iodine, and selenium are today's dire need of the world through improved input use efficiency. The recent studies advocated the grain yield enhancement of rice and wheat with soil application of $ZnSO_4$ at 50 kg/ha under zinc-deficient soils but enhancement in grain zinc concentration is only 2–3 mg/kg. Using foliar zinc sulphate heptatehydrate at 0.5% at earing and early milk stage appreciably improves the Zn concentrations by 35% in rice and about 100% in wheat. The foliar Zn application along with pesticides which are required to control insects and diseases in wheat and rice can also be used without any adverse effect on the crop, it not only enhances grain Zn and controls insects and diseases but also reduces the application costs of the chemicals. A mixture of the micro/trace elements (zinc sulphate, potassium iodate, and sodium selenate) can be used together to enrich these nutrients together in rice and wheat. The optimum nitrogen application directly enhanced the protein, zinc, and iron in the grains. Overuse of phosphorus fertilizer may

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hamper the absorption of zinc through roots due to negative interaction. But integrated nutrients management using organic manure along with chemical fertilizer directly affects the micronutrients uptake and grain yield of the crops. Some of the varieties of rice, wheat, pearl millets that have been developed through genetic biofortification are also being consumed in the developing world for meeting the micro/trace elements requirement of masses. So, integration of genetic and agronomic biofortification can improve the nutrient use efficiency which enhances the nutrient content in the grains and will help in mitigating the deficiency of nutrients in crops and human beings across the globe.

Keywords

Biofortification · Integrated use of inputs · Micronutrients · Nutrient use efficiency

14.1 Introduction

Approximately one-third of the human race is facing the micronutrients deficiencies like iron (Fe), zinc (Zn), selenium (Se), and iodine (I) which pose serious health problems. These deficiencies are more prevalent in developing nations including India, Pakistan, Afghanistan, etc. Hidden hunger or deficiencies of these micronutrients are an important form of undernourishment. The hidden hunger reduces the gross domestic product of the developing world up to 5% by posing serious health concerns along with fiscal encumber on social health caring system. Human micronutrient deficiencies occur usually on the world map where soils are either deficient in these micronutrients or didn't supply these nutrients in the available form to plants. It has already been advocated by many researchers that human Zn deficiency geographically overlaps with soil Zn deficiency. The overlap map of soil micronutrients deficiency and human micronutrients deficiency can explain that the products made from agricultural produce are the foremost resource of human nutrition in these countries. To date, the major aim of world agriculture is to produce more tonnage of the food to tackle the hunger problem and famines which over gaze to accomplish better nutrition by supplying healthy food. It is clear from the studies that vegetarian diets including cereal grains, like wheat, rice are, however, innately poor in micronutrients to meet sufficient human nutritional needs. The major functions of these nutrients in human beings (Ram et al. 2016a) are

1. Zinc is available in all cells of the human body which is required to improve the body's immune system. Even a recent report to develop an immune system against COVID-19 was also reported from China.
2. About 70% of Fe is found in red blood cells that help to carry oxygen to various cells so Fe is needed for blood production.
3. Iodine deficiency disorder (IDD) is one of the major human health issues. Goitre and hyper and hypo-thyroids are also major disorders found in masses across the globe.

Table 14.1 The present concentration of zinc, iodine, selenium, and iron in grains of rice and wheat

Crop	Zinc (mg/kg)	Iodine (μg/kg)	Selenium (μg/kg)	Iron (mg/kg)
Rice	10–15	15–25	100–450	10–15
Wheat	20–30	10–15	45–550	25–30

Data source: Zou et al. (2019)

Table 14.2 Daily per capita requirement for an adult human being for different micronutrients

Micronutrient	Daily per capita requirement
Zinc (mg/kg)	11–13
Iron (mg/kg)	8–27
Iodine (μg/kg)	90–250
Selenium(μg/kg)	55–70

Data source: Zou et al. (2019)

4. Selenium (Se) is needed in minute quantities to manufacture proteins called antioxidants enzymes. Se also helps to prevent some types of cancers in the human body.

The staple food rice generally contain 10–15 mg/kg Zn, 10–15 mg/kg Fe, 15–20 μg/kg I and 100–450 μg/kg Se (Table 14.1). Whereas wheat grains contain 20–30 mg/kg Zn, 25–30 mg/kg Fe, 10–15 μg/kg I and 45–550 μg/kg Se (Table 14.2). As Se is easily absorbed by the plants from the soil, so the Se available sources in soil affect the Se content in rice and wheat. The low content of Se in the cereal grains is often linked with low Se concentrations in soils as reported from different countries. However, few villages (Barwa, Baghauran, Simbli, etc.) in Shaheed Bhagat Singh Nagar of Punjab in India contain higher Se content by which several toxic effects were observed in the area like *Selenosis* in cattle (Dhillon and Dhillon 2020).

14.2 Reasons for Low Micro/Trace Elements in Human Being

Globally, it is widely recognized that micronutrient deficiencies in humans are more prevalent where cereal-based foods are the major source of energy and secondly inadequate dietary intake of micronutrients by the population. (Table 14.1).

The available content of these nutrients in rice and wheat cannot fulfill the daily need for these nutrients for human beings. The normal adult man requires about 11–13 mg Zn, 8–27 mg Fe, 90–250 μg I, and 55–70 μg Se per capita (Table 14.2). The range for children is on the lower side whereas a range of these nutrients is on the higher side for pregnant and lactating women. Wheat and rice are important sources for the micro/trace elements and accounts for 70% and 55% of per capita calories intake, respectively of the people living in rural areas.

Due to augmented cropping intensity and use of only major nutrients fertilizer, not practicing organic manuring including green manures, lowered these macronutrients as well as micro-nutrients in soils and their availability which made 48% of

Indian soils deficient in available Zn (Singh 2011). However, under Punjab conditions, farmers regularly apply zinc sulphate fertilizer to rice crops at 25–30 kg/ha which reduces Zn deficiency from 43% to 21% in 2010 (Sadana et al. 2010). At the moment, increasing micronutrient concentration in grains represents a very important challenge that can be achieved by using genetic and fertilization approaches. Kapil and Jain (2011) reported that in India about 61 million children (43.8%) are Zn deficient and this deficiency problem was 51.3% in Orisha, followed by 48.1.% in Uttar Pradesh, 44.2% in Gujarat, 38.9% in Madhya Pradesh, and 36.2% in Karnataka (36.2%).

14.3 Correction of Micronutrients Deficiency in Human Being

Micronutrient deficiencies in human beings can be corrected by adopting two options, i.e., (1) through food supplements viz; oral syrups, capsules/tablets, injections, etc., and (2) consuming a micronutrients-enriched diet. Higher strata of the community can purchase the supplements whereas the people living below the poverty line (BPL) cannot afford that for taking care of micronutrients deficiency. The “Food security Bill” passed by the Government of India, in which people BPL could get the food grains through the public distribution system, streamlines the food grain distribution system due to which about 50% of the population have the right to avail the foodgrains. Under such conditions, to alleviate micronutrients deficiency in the population, it will become vital to provide the micronutrients enriched food grains to the people. Thus, enriching staple cereal grains with micronutrients by adopting agricultural tools is considered a promising approach to alleviate micronutrient deficiency in humans. The Harvest Plus Program (www.harvestplus.org) running projects in different countries to develop micronutrient enriched varieties of especially cereal food crops. Harvest Plus is also running a twin project on Global Zinc Fertilizer Project to enrich micro/trace elements in cereal grains through fertilizer strategy across the globe (Harvest Zinc).

14.4 Enriching Cereal Grains with Micronutrients

Enriching the cereal grains with Zn can either be achieved by genetic biofortification (breeding of Zn enriched varieties of cereals) and/or agronomic biofortification (utilizing Zn-containing fertilizers for crops). Till the development of Zn-rich new varieties and their adoption by the farmers, the micronutrient deficiency can be taken care of by agronomic biofortification. Agronomic biofortification can be used in different crops for enriching them with micronutrients. The biofortification approach should be successful only if: (1) it improves or attains similar yield as in locally adapted genotype (2) the micronutrient density in grains must have a visible positive influence on human health; and (3) the micronutrient concentrations should be independent of environmental conditions (Welch and Graham 2004).

14.5 Agronomic Approaches for Biofortification

14.5.1 Zinc Use Efficiency under Different Fertilization Application Timing and Methods

The uptake and efficiency of any supplementary nutrient for crop performance are generally affected by the kind and level of fertilizers, along with their application method. The micronutrient bioavailability, as the nutrients form may have a synergistic, neutral, or even antagonistic influence on crop productivity and nutrient use efficiencies (Rietra et al. 2015). The use of micronutrient-containing fertilizers as foliar sprays improves nutrient absorption and effective reallocation in the eatable plant parts than soil application of fertilizers, especially in food grains and fresh green vegetables (Lawson et al. 2015; Kumar et al. 2021). Foliar Zn application at 0.5% $ZnSO_4.7H_2O$ significantly increases the wheat grain Zn concentration as compared to soil application (Zou et al. 2012). Wheat grain Zn concentration, not only in whole grain but also in the endosperm, could also be increased with optimum application time and its concentration of foliar Zn formulation. In the recent past, substantial achievement had been made in enhancing the cereal grain Zn, particularly in wheat, through foliar Zn fertilization (Cakmak 2008). Foliar Zn application in wheat at early milk as well as dough stage was more effectual in elevating zinc grain including endosperm, while soil zinc applications remained poor effective (Cakmak et al. 2010a). It was also observed that spray of $ZnSO_4.7H_2O$ slightly improved the grain yield instead of having any adverse effect on the crop. But Karim et al. (2012) recorded that under drought conditions; wheat responded positively to foliar Zn application for plant growth and development of antioxidative defense mechanisms, against drought-induced oxidative cell damage even in soil having high available Zn.

14.5.2 Soil Application, Foliar Application, and Seed Priming

Habib (2009) reported that the wheat grains' Zn concentration gets enhanced by three folds with the foliar Zn application at earing to grain development stages of the crop. For enriching micronutrients in grains, the combined application of soil and foliar application was found to be the most efficient technology (Cakmak et al. 2010a; Phattarakul et al. 2012). Foliar application is significantly effective in improving the absorption of micronutrients into the plant because micronutrients especially Zn is phloem transported nutrients. The foliar fertilizers application is costly, gets washed away easily by rain (Garcia-Banuelos et al. 2014) with no or little yield advantage (Ram et al. 2015). Defined micronutrient application through seed priming or treating seed with Zn fertilizers can enhance plant development resulting in improved productivity, but Zn enriched grains are not found (Duffner et al. 2014; Rashid et al. 2019; Kumar et al. 2021). Zou et al. (2012) recorded from 23 locations of seven countries that the Zn concentrations of grains increased by 21 or 22 mg/kg either with 0.5% foliar Zn application or integrated with soil application of 50 kg $ZnSO_4.7H_2O$/ha. The soil zinc application improved both

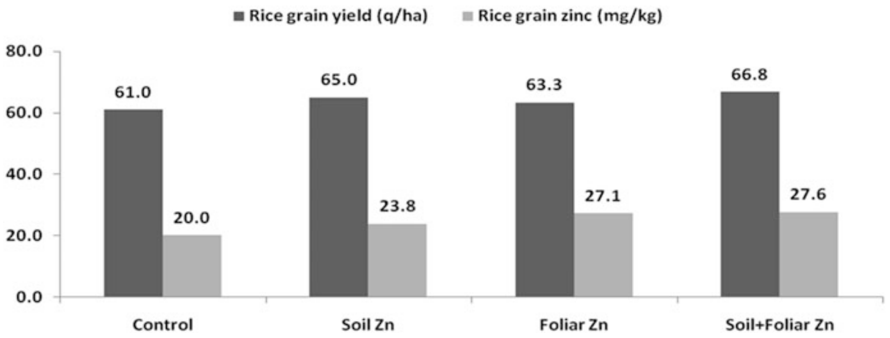

Fig. 14.1 Rice productivity and grain Zn content in rice (Adapted from Phattarakul et al. (2012)

wheat productivity and wheat grain Zn concentration in Central Anatolia, which is a highly Zn-deficient area of Turkey (Ekiz et al. 1998). They reported an almost two-fold increase of grain Zn in *durum* wheat with soil Zn fertilization, whereas there was a three-fold increase when Zn fertilization was applied through soil application followed by foliar spray. Graham et al. (1992) in Australia and Shiway et al. (2008) also reported an increase in grain zinc concentration in wheat by applying zinc through soil application. In brown rice, soil Zn application had a less increasing effect on Zn concentrations in the Philippines, whereas the foliar Zn fertilization gave a more promising outcome by enhancing Zn content in wheat grains (Wissuwa et al. 2008). It was reported in studies of five countries, that soil Zn application enhanced the grain yield by 5% (Phattarakul et al. 2012) (Fig. 14.1). Furthermore, grain Zn concentrations were significantly improved with foliar Zn fertilization (32.3–34.7 mg/kg) when Zn fertilization was done after ear emergence at early milk along with dough stages across different genotypes and locations. However, from the Philippines reports are available that rice genotypes responded differently to foliar Zn treatments doe enriching grain Zn (Wissuwa et al. 2008). Wei et al. (2012) summarized that for enhancing the bio-available Zn in rice, the most promising approach is foliar Zn fertilization. They further advocated that $ZnSO_4$ and Zn-amino acids are admirable foliar Zn forms for successful agronomic biofortification. Foliar application of $ZnSO_4$ at 0.5% at boot and early grain development was found to be effective in increasing grain Zn from 20 ppm to 40 ppm in rice (Ram et al. 2015). Foliar Zn fertilization helps to manage biotic stress along with improved grain Zn concentration (Ekiz et al. 1998). Pooniya et al. (2012) also summarized that the combined application of Zn through the soil and foliar sprays helps in ameliorating Zn deficiency in rice. It was reported that foliar zinc fertilization increased the rice, wheat, and maize grains Zn by 30, 25, and 63%, respectively higher, as compared to soil Zn fertilization (Wei et al. 2012; Yerokun and Chirwa 2014). Ghasal et al. (2017) reported that Zn absorption gets improved by 4–7% with the foliar application over the soil application.

14.5.3 Nutrient Use Efficiency and Interaction with Other Nutrients

The grain yield of most of the annual crop plants is influenced by nutrient interaction which is considered as one of the most important factors affecting crops. Nutrient interaction can be positive, negative, or neutral. These nutrient interactions may occur at the root surface or within the plant. The root surface interactions are due to the chemical bonding of ions and the precipitation of some other compounds.

14.5.3.1 Nitrogen

Some major nutrients help in the absorption and remobilization of minor nutrients within the plant. The Zn and Fe fertilization along with nitrogen (N) as soil or foliar sprays enhanced the grain yield as well as the uptake of these nutrients (Cakmak et al. 2010b; Kutman et al. 2011a). Crosstalk between Zn and N has been widely reported and recent research results had confirmed a constructive effect of Zn nutrition in enhancing the grain and foliage N content in various crops (Gupta et al. 2016; Cakmak and Kutman 2018; Khokhar et al. 2018; Kumar et al. 2018). Pal et al. (2019) observed that foliar 2% urea and 0.5% $ZnSO_4$ application at flowering and pod formation stage resulted in a 16 per cent increase in Zn content in chickpea grain than the sole application of Zn at flowering and pod formation stages. Foliar application of $ZnSO_4$alongwith urea improves the absorption and movement of Zn from roots to shoot resulting in higher zinc content in chickpea grains. Nitrogenous fertilizers improve the remobilization of Zn accumulated in the source (vegetative tissues) to the sink (grains) through the phloem. In wheat, Kutman et al. (2010) also recorded similar results that 2% urea application at ear initiation and early milk stages was found to be promising in enriching the grains with Zn content. The increased nitrogen nutrition of the plants helps to enhance the uptake by root, improves its movement from root to shoot, and remobilization of Zn in the plant (Erenoglu et al. 2011). It is well known that Zn regulated transporters proteins facilitate the enhancement of various plant activities like loading and unloading of xylem and phloem, xylem-to-phloem exchange, and addition of Zn in grain (Curie et al. 2009).

Barunawati et al. (2013) while working on wheat reported that 2-deoxymugineic acid (metal-chelating compounds) help in Zn and Fe translocation from flag leaves to wheat grains. Kutman et al. (2011b) also reported that with increased N rates, 80% and 60% of shoot Zn and Fe, respectively, got remobilized to the wheat grains. Similarly, Erenoglu et al. (2011) also advocated the significant function of N in enhancing the uptake and density of Zn in food grain crops. The positive correlation between nitrogen, zinc, and iron for the increased amount in wheat grains helps in the improvement of multiple micronutrients simultaneously (Cakmak et al. 2010b). The positive impact of N in speeding the uptake, movement, and buildup of micronutrients, particularly Zn and Fe in cereal grains, has been broadly studied, and reports are accessible (Singh et al. 2018; Pearson et al. 2016). Sulfur (S) is an additional nutrient that was frequently reported in enhancing Fe and Zn nutrition in plants. The plant's capacity to absorb and accumulate iron was confirmed to be dependent upon the S content of soil used in raising cereal crops (Zuchi et al. 2012).

The encouraging influence of soil or foliar Fe application on Fe concentration was noticeable under better nitrogen nutrition. Increased nitrogen concentration has encouraging impacts on root absorption, shoot transportation, and seed accumulation of zinc and iron. So results propose that N application has a constructive relationship with Zn content in the plant.

14.5.3.2 Phosphorous

Zn had a significant negative interaction with phosphorus (P) uptake. Studies by other researchers (Aref 2012) confirmed that P uptake in the shoot and its content in the leaves decreased due to Zn sufficiency in plants. Zn can act together with inorganic phosphate in the formation of insoluble $Zn_3(PO_4)_2$ in the soil and construct it unavailable for root uptake and exhibit a negative correlation concerning Zn-P crosstalk (Gupta et al. 2016). However, the reports of synergism and antagonism in Zn and P are also available (Fageria 2002). Oseni (2009) reported low cowpea yield due to Zn – P interaction when P was applied in combination with Zn. The recorded effects could be ascribed to the fact that the P application reduces the Zn availability for optimal plant growth. Rathore et al. (2015) observed that the interactive effects of P and Zn in most of the sampling stages of rice and mungbean showed an increase in P concentrations when the doses of Zn have increased in combination with the doses of P. This antagonistic effect of P and Zn may be because high soil available P or high rates of P application may imbalance the Zn availability, slowed down Zn movement from roots to shoot; the gathering of Zn in roots and metabolic anarchy in the plant cells.

Excessive use of phosphatic fertilizers may cause precipitation of insoluble Zn phosphate which results in incipient Zn deficiency in plants (Zingore et al. 2008). For enhancing the micronutrient fertilization use efficiency the most vital factors are proper nutrient management and integrated soil fertility management approach. Not only do the major nutrient fertilizers increase the micronutrient fertilization use efficiency, but also other soil physical, chemical, and biological properties play a critical function in optimizing the nutrient use efficiency. Paramesh et al. (2020) observed an increase of zinc and iron in wheat grains by applying half P by P enriched compost + remaining half P from phosphatic fertilizer along with the application of zinc sulphate heptahydrate at 12.5 kg/ha and one foliar application of 0.5% Zn by dipping the binding effect of P on Zn. So, high P fertilization may hinder the Zn use efficiency in the plants. The grain Zn concentration was unaffected because of the organic P application whereas inorganic P fertilizer application reduced the grain zinc concentration.

14.5.3.3 Potassium

In a few studies, the higher amount of available K in the soil improves root growth with Zn fertilization and led to better absorption and transportation of K from the rhizosphere to plant parts. In Pakistan, Anees et al. (2016) recorded a supplementary relationship between zinc and potassium contents in rainfed maize grown conditions. Zinc fertilization didn't affect the K content in cowpea haulm both in the major and minor seasons, however, grain K content was significantly affected by the Zn fertilizer application (Chakirwa et al. 2019). Jat et al. (2014) reported no interaction between potassium and zinc in wheat. They reported better K and Zn nutrition improved the uptake and grain nutrient content in wheat.

14.5.3.4 Farmyard Manures

Incorporation of organic resources of plant nutrients helps to alter the soil physical conditions like arrangement of solid particles of soil, the capacity of soil particles to retain cations and water by improving the soil organic content (Van-Noordwijk et al. 1997; Yadav et al. 2020), soil fauna & flora and sustained nutrient release. However, in synchronizing the need and supply of nutrients to plant, mineral fertilizers provide litheness in the timing, placing, and application rate of nutrients. Enhancing the soil organic matter by incessant incorporation of plant and animal remains not only increase the total zinc concentration in the soil but also enhance its availability to plant by solubilizing the Zn content (Santos et al. 2010; Manzeke et al. 2014; Meena et al. 2020). For supporting the nutrient balance and alleviating the micronutrient where nutrient-rich organic manures are not available, the combined use of organic manures along with inorganic micronutrient fertilizers plays an important role. The integration of mineral fertilizers with organic matter improves the agronomic efficiency of mineral fertilizers (Vanlauwe et al. 2010). Ali et al. (2011) reported the biological yield enhancement when P–humate and Zn–humate is applied in combination rather than their sole application. Similarly, Paramesh et al. (2020) found that integration of compost and inorganic fertilizer recorded appreciably higher grain yield, straw yield, protein, and micronutrients content.

14.5.3.5 Integrated Nutrient Management

Efficacy of agronomic biofortification and grain yield enhancement could be achieved through the combined application of micronutrients and macronutrients as they interact with each other. The use of organic sources along with mineral fertilizer and improved germplasm is very important to enhance their fertilizer use efficiency (Vanlauwe et al. 2010). Integrated nutrient management not only enhances their effectiveness but also has harmonizing functions and enhances mutual effectiveness. Manzeke et al. (2014) recorded higher Zn concentration in the maize grain and grain yield where Zn fertilizer was used jointly with FYM and leaf trash of forest.

Well-nourished plants with N and P can have improved root systems, transportation, and reallocation of plant nutrients from source to sink (Prasad et al. 2014). In the wheat grain endosperm, an elevated concentration of zinc and iron was observed where the nitrogen application rate was higher (Kutman et al. 2011b; Shi et al. 2010). It has also been reported that, in wheat, fertilization with Zincated nitrogenous and phosphatic fertilizer enhances the wheat grain yields (Cakmak 2004). Hence, the INM along with genetically improved genotypes enhances the best possible nutrient use efficiency, when the cultivar is selected to have better nutrient uptake and accumulation in the edible part of the crop examples of PBW 1 Zn variety of wheat in India.

14.5.3.6 Simultaneous Use of Zinc, Iodine, Selenium, and Iron

The yield of sorghum and finger millet, as well as nutrient uptake (N, P, Zn, Boron, Sulphur), were improved significantly with the application of nitrogenous, phosphatic, and potassic fertilizers blended with micronutrients like Zn, B, and S (Rao et al. 2012). However, due to a dilution effect, the application of phosphatic fertilizers lowers the micronutrient concentrations when the plants grow prolifically and give better yield (Singh et al. 1988). Niyigaba et al. (2019) reported three times increase in grain crude fiber by 60% $ZnSO_4$ + 40% $FeSO_4$ (5.5 kg/ha of 80% $ZnSO_4$ + 20% $FeSO_4$) application. Also, Zn fertilizer application not only enhanced Zn concentration in grain but also the iron content in the grain. Further, they found that for increasing the crude protein content, 80% $ZnSO_4$ + 20% $FeSO_4$ (5.5 kg/ha of 80% Zn + 20% Fe) is the most appropriate amalgamation.

The success of agronomic biofortification is effective with Zn and Se (Cakmak 2014). Although grain yield increase was not realistic with Se-enriched fertilizers application improved maize and wheat grain selenium concentrations were observed. In Finland, on average, at the national level, 15 – fold increase in selenium content in cereal crops with the addition of 15 mg Se/kg to NPK fertilizers was quoted. This is the reason; the Finnish people's Se intake is well above the recommended nutrition (Alfthan et al. 2015). In Australia, 133-fold and 20-fold increase of Se concentration in wheat grain was reported with Se application of (4–120 g Se/ha) in wheat as soil and foliar application, respectively. Another researcher also recorded that the application of Se fertilizer has a positive correlation with its bioavailability to the maize (Chilimba et al. 2014) as well as in flour and bread of wheat (Hart et al. 2011). Keeping in view the health of human beings and crop productivity, all the current research projects are focused on Zn micronutrients, as deficiency of Zn is common in humans and an important crop yield-limiting factor. Turkey is the leading nation reporting that cereals like wheat, maize, sorghum, barley, pulses like soybean, pea, common bean, and oilseed like safflower, canola crops achieve higher productivity and grain Zn concentration if Zn fertilizers were applied (Cakmak et al. 2010a). Yilmaz et al. (1997) in their studies found that both soil and foliar application of zinc results in a three-fold increase in wheat yields and wheat grain Zn concentrations. Field studies in India proved similar results in rice with the use of Zn-enriched urea (Cakmak 2009). The impact of the soil and foliar Zn fertilization with zincate fertilizers in ten African countries resulted in 23%, 7% & 19% and 30%, 25% & 63% enhancement of Zn in maize, rice, and wheat grains, respectively (Joy et al. 2015). Zn fertilization also upshot the next crop generation by increasing its productivity by having better growth and development and strength to combat environmental stresses. Furthermore, Zn availability for human consumption could be enhanced through Zn fertilization as it mobilizes the phytate in grains (Hussain et al. 2013).

Iron is a highly immobile micronutrient as compare to Zn and Se, as it precipitated into insoluble forms in the soil so plants are unable to absorb it. Cakmak et al. (2010a) in their studies on wheat found that grain Zn concentration got enhanced with Zn application while Fe concentration was not improved to the greater extent after Fe application. For Fe enrichment in the crops, foliar application

Table 14.3 The effect of the application of zinc on grain yield and grain zinc content of wheat in India

Character	Treatment			
	Control	F Zn	Foliar I	F CT
Grain yield	54.50	57.33	54.17	52.00
Grain zinc	28.6	43.9	35.7	47.1
Grain Fe	29.5	29.8	31.5	32.8
Grain iodine	12		476	246
Grain selenium	406	–	–	601

Source data: Zou et al. (2019)

of mineral Fe is the best agronomic approach. Shahzad et al. (2014) in their experiment on rice and wheat observed that foliar Fe application caused enhanced the Fe concentrations in grains. However, in some studies plants didn't respond to foliar Fe application.

Agronomic biofortification through foliar application of micronutrients has to pay attention to a single or sometimes two micronutrients in almost all studies in all the food crops. Mao et al. (2014) in China studied the effects of the Se and Zn application technique and observed that Se concentration is superior when it is applied via soil followed by integrated foliar Zn and Se application. Similar results were recorded by Mangueze et al. (2018) for rice cultivars in Mozambique. They recorded that zinc and selenium foliar application together significantly enhanced their concentrations in whole grain as well as in polished grain.

In India, two-thirds of the energy people are obtaining from rice and wheat. To meet the daily calorie intake, the rural population depends upon wheat which alone contributes up to 70% and is simultaneously the main source of Zn for the individuals residing in the emergent nations. For the third world, along with food sufficiency, due attention should be paid to nutritional security. Zou et al. (2019) used a mixture of micro/trace elements as a cocktail to enrich Zn (0.5% $ZnSO_4 \cdot 7H_2O$), I (0.05% KIO_3), Se (0.001% $NaSeO_4$) and Fe (0.2% FeEDTA) together in wheat and rice and observed 53.5% increase in grain-Zn with sole Zn application whereas 67.7% increase with micronutrient cocktail spray (Table 14.3). They further found that the sole application of foliar I gave 464 μg/kg higher I content whereas micronutrient cocktail gave 234 μg/kg increase in grain I as compare to without I application. Similarly, with foliar application of micronutrient cocktail, an increase in grain selenium content from 406 μg/kg to 601 μg/kg and 11.2% grain Fe content was observed. However, foliar application of micronutrient cocktails is a successful approach to enrich wheat with I, Zn, Se, and partly Fe with a minor reduction in wheat grain yield (4.6%). With a single foliar application, three micro/trace elements can be enriched which also minimizes the cost of cultivation.

14.5.3.7 Foliar Fertilization with Pesticides

Motivating the farmers for foliar Zn application on rice and wheat crops for enriching the grain Zn concentrations to manage the hidden hunger. As there is no visible advantage to the farmers, neither the increased grain yield nor they get more price for high Zn grains, thus the farmers will not be inspired to follow the foliar Zn application as this practice will also affect the cost of cultivation. Grain yield enhancement will not be achieved with sole Zn application at early milk stage whereas combined application of 0.5% $ZnSO_4.7H_2O$ and pesticides like dimethoate for aphid control and propiconazole for rust control at ear initiation stage to early milk stage gave yield enhancement in case of wheat. Similarly, the use of different pesticides in rice can also be explored.

Previous studies showed that the Zn-enriched seeds have higher seedling vigor which results in a good crop stand that might attract the farmers to enrich the preceding crop with Zn. The compatibility of Zn with the existing pesticides, which are required at the time of heading, which results in yield enhancement may attract the farmers for adding Zn. Nowadays, farmers are using some pesticides for the control of fungal diseases like yellow rust and insect pests like aphids. Ram et al. (2015) studied the effect of combined application of soil and foliar Zn with or without propiconazole on Zn deficient soil. They found that combined application of soil + foliar Zn and soil Zn + foliar Zn along with propiconazole recorded 24.3 and 28.1% enhancement in wheat grain yield on Zn-deficient soils. The higher grain yield in propiconazole treatment was due to better control of yellow rust in this treatment. Whereas, the grain Zn enhancement of 114.7 and 102.7% were recorded in soil + foliar Zn application and soil + foliar + propiconazole, respectively. These results show the possibility of using propiconazole along with foliar Zn for dual purposes. We further found that combining fertilizer and pesticides is more economical than fertilizer alone if no premium price is available. Ram et al. (2015) further found that on Zn enriched soils, soil + foliar Zn application and soil+foliar +propaconazole recorded 4.0 and 5.5% enhancement in wheat grain yield (Fig. 14.2). The less increase in grain yield was due to Zn sufficient soils. However, the grain Zn enhancement of 88.5 and 78.5% higher was found in soil + foliar Zn and soil Zn + foliar Zn + propiconazole as compared control plot respectively. Zn deficient soils respond better to Zn application resulting in Zn enhancement in grain as compared to soils having sufficient Zn content.

Ram et al. (2016b) further found, increased grain yield of 1.1 and 1.6% in wheat and 0.6 and 02% in rice as compared to the control plot. The enhancement in grain Zn was found to be 42.6 and 38.4% in wheat and 44.4 and 33.8% in rice under foliar Zn and foliar Zn + fungicide respectively, which also shows the compatibility of the Zn and propiconazole for making tank-mix.

14.5.3.8 Crop Performance High Zn Seed

Rashid et al. (2019) conducted an experiment on crop establishment and productivity using Zn enriched seeds. Further, they reported that in comparison to the normal seed Zn, soil Zn fertilizer application improved wheat productivity by 8.9% and rice grain yield by 8.4%. (Fig. 14.3) Zn-enriched seeds also gave better wheat grain yield by 7.7% and rice grain yield by 2.7% in comparison to the control treatment. Across the locations and 2 years, Zn-enriched wheat seeds enhanced crop emergence by 4%. This study confirmed that the seeds enriched with Zn increased wheat and rice productivity also so, the use of high-Zn seeds in the next cropping year can give the advantage to improve crop yield with less cost.

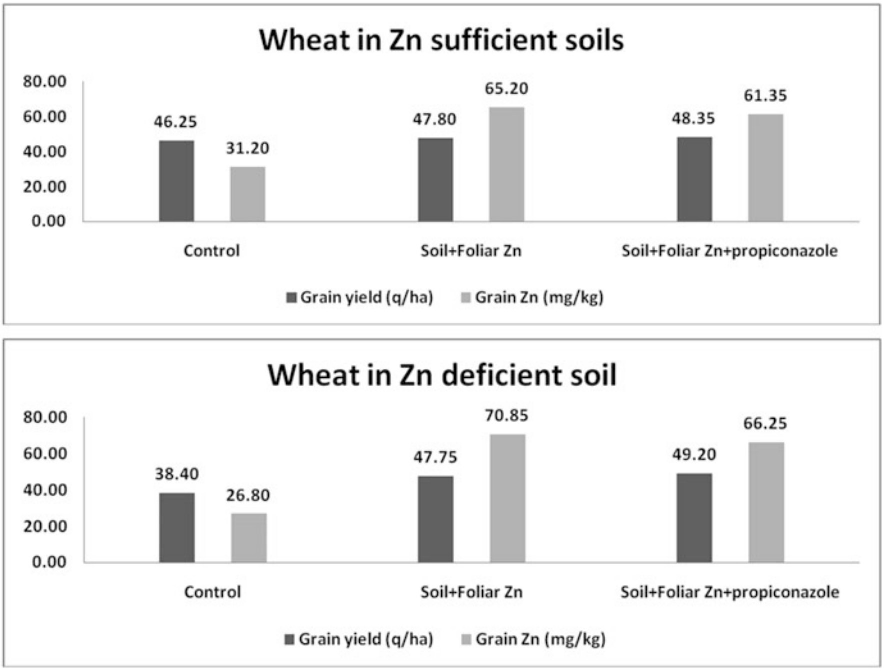

Fig. 14.2 Wheat grain yield and grain Zn concentration with the use of zinc sulphate fertilizer with pesticide on Zn sufficient and deficient soils [Adapted from Ram et al. (2015)]

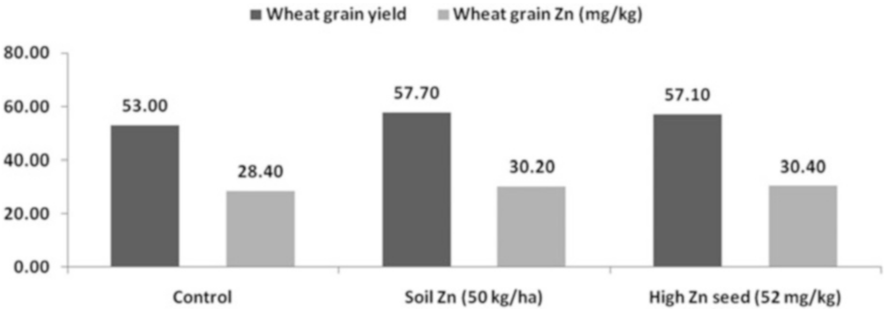

Fig. 14.3 Wheat grain yield and grain Zn concentration (Adapted from Rashid et al. (2019)

14.6 Genetic Approaches for Biofortification

Various genetic means, such as conventional breeding, molecular mapping, marker-assisted selection, genome-wide association selection (GWAS), genome editing, and genetic transformation, have been widely employed for the quality improvement in wheat. In addition to crop yield improvement, the quality improvement including micronutrients like Zn, iron, and selenium in the grain helps to achieve the food security of the world's growing population. It is well known that quantitative traits are not easy to transfer as compared to qualitative traits to breed through conventional breeding methods. But some widely grown cultivars like *Triticum aestivum spp spelta* and *Triticum turgidum spp dicoccon* have shown significantly better quality traits that can be transferred to locally adapted highly productive wheat varieties (Velu et al. 2013). In the long run, genetic approaches are considered to be a more feasible solution for alleviating nutritional deficiencies. Determining the order of nucleotides on DNA, bioinformatics, and new experimental methods, regions within the wheat DNA accountable for quality traits including micronutrients could be identified (Klimenko et al. 2010; Zhang et al. 2017). Saini et al. (2020) reported the identification of 325 QTLs for grain protein content, 131 QTLs for iron, Se, and Zn content, and 83 QTLs for yellow pigment content, which can be used for further improvements in quality traits in wheat.

In one of the studies, 369 elite European wheat genotypes were recognized with 41 traits related to their iron content, the majority of which were located on chromosome 3B. The 123 synthetic hexaploid kinds of wheat (smaller panel) were used to recognize three marker-assisted trait combinations for iron and 13 for Zn (Bhatta et al. 2018). The Punjab Agricultural University (Ludhiana, India) and Indian Institute of Wheat and Barley Research (Karnal, India) have released Zn biofortified wheat varieties. The Zn biofortified wheat variety Zinc Shakti (genes from *Ae. squarrosa* used in PBW343), 'Zincol 20,160 (genes from *T. spelta* in NARC2011) and WB 02 and PBW 1 Zn (genes from *Ae. squarrosa* and *T. dicoccon*) were having 40%, 25%, 20%, and 20% increased Zn content in their grains, respectively (Tiwari et al. 2009).

14.7 Integrating Genetic and Agronomic Approaches

After taking the lessons from wheat and rice we also conducted foliar Zn application in *durum* wheat and triticale varieties along with bread wheat cultivars. In which Dhaliwal et al. (2019) studied the foliar application of heptahydrate zinc sulphate at 0.5% on eight bread wheat, three *durum* wheat, and four triticale genotypes for 2 years in comparison to the control plot. They found better grain yields of bread wheat (43.6 to 56.4), triticale (46.5 to 51.6), and *durum* wheat (49.4 to 53.5) varieties with foliar Zn application. Among the varieties, wheat (PBW 550), triticale (TL 2942), and *durum* (PDW 291) gave 5.22, 4.24, and 4.56% higher productivity as compared to control treatment. They further found that foliar Zn application enhanced grain Zn in bread wheat, triticale, and *durum* wheat cultivars from 31.0 to 63.0, 29.3 to 61.8, and 30.2 to 62.4 mg/kg, respectively. So, agronomic biofortification is equally effective in all *durum* wheat, bread wheat, and triticale grains also. It is confirmed that agronomic Zn biofortification through foliar Zn application is an efficient means in enriching the grain Zn of genotypes with strong Zn-remobilization ability as compared to weak Zn mobilizers (Mabesa et al. 2013). Ram et al. (2019) found that enhancement in grain Zn with foliar Zn application was better in all biofortified wheat varieties like PBW 1 Zn in India and NR 488 in Pakistan. But we could not found the grain Zn concentration of toxic levels. Sovagronomic and genetic biofortification are complementary to each other for enriching grain Zn. Even the mixture of the micro/trace elements can be used in Zn biofortified genotypes.

14.8 Conclusion and Future Perspective

Zinc, Fe, I, and Se are important from the human health point of view. So a sufficient intake of these micro/trace elements is required. Artificial intake through injections, tablets, and supplements is not economical. So, biofortification of major food crops is the dire need of today's world. The literature reviewed advocated that soil application of zinc sulphate fertilizer (50 kg/ha) improved the grain yield of rice and wheat under zinc-deficient soils. Soil application of zinc fertilizer in rice and wheat enhances grain zinc concentration only 2-3 mg/kg. Foliar Zn application (0.5% ZnSO4.7H2O) at the earing and early milk stage significantly increased the Zn concentrations over the control and soil-applied zinc fertilizer. The enhancement is 35% in rice and about 100% in wheat. Foliar Zn application (0.5% $ZnSO_4.7H_2O$) along with pesticides in wheat and rice can also be used without any adverse effect but also reduce the application costs of the chemicals individually. Better seedling vigor and good crop establishment should be obtained from seeds having high Zn content. The mixture of the micro/trace elements (zinc sulphate, potassium iodate, and sodium selenate) can be used together to enrich these zinc, I, and selenium together in rice and wheat. N application directly enhanced the zinc uptake in the grains. Although, the use of higher phosphorus may hinder the absorption of zinc through roots. The use of farmyard manure and integrated nutrients management has an affirmative impact on micronutrients uptake and grain yield of the crops. The genetic means of biofortification is more important for meeting the micro/trace elements requirement of masses. Integration of genetic and agronomic biofortification can improve the nutrient use efficiency by enhancing the nutrient content in the grains and will help in mitigating the deficiency of nutrients in crops and human beings.

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Enhancing Water Use Efficiency for Food Security and Sustainable Environment in South Asia

15

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and Yadvinder-Singh

Abstract

The future of Indian agriculture is at risk due to constantly depleting aquifers and increasing pressure on surface and ground water resources. In this chapter, we have synthesized the information on different water management approaches, irrigation scheduling, and the impact of conservation agriculture (CA) based crop management practices on irrigation water saving and water productivity (WP) in both rainfed and irrigated ecosystems. A single approach for irrigation management will not be capable to achieve the approaching challenge of generating '*More Crop Per Drop* and also contributing to the *'Jal Shakti'* mission of the Government of India. Integration of irrigation technologies (water-saving methods, irrigation scheduling approaches, etc.) with new resource conservation technologies are essentially required to harness the full potential of available irrigation water for achieving higher WP and profitability in dominant cereal-based systems on a sustainable basis. Improved irrigation management practices (amount and time) and methods (micro-irrigation, surface, sub-surface drip) based on real-time monitoring of crop-soil moisture are required to increase the WP by efficiently managing the water resources. Studies showed that CA-based practices are gaining momentum in India and elsewhere and have helped improving resource use efficiency including WP. Limited studies on water management practices under CA have demonstrated complementarities of coupling these practices for conserving the soil water by reducing evaporation, and improved crop yields, which ultimately increased the WP. In the future, we got to increment logical knowledge of the impacts of agronomic practices on WP over different soil types and agro-climatic situations to enhance WP of cropping system as a

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whole by using micro-irrigation methods coupled with irrigation automation techniques. With an increase of salt concentration within the water, declining grain yields and weakening soil health have been broadly observed. Similarly, there is a need to plan long-term irrigation expansion policies using poor-quality saline/sodic ground waters to sustain yields and increase the WP.

Keywords

Crop residue · Cropping systems · Salt concentration · Sub-surface drip · Water dynamics

Abbreviations

AW	Alkali water
CA	Conservation agriculture
CPE	Cumulative pan evaporation
CRI	Crown root initiation
CT	Conventional till
CT	Conventional tillage
CW	Cotton Wheat
DI	Deficit irrigation
DSR	Dry seeded rice
EC	Electrical conductivity
Es	Soil evaporation
ESP	Exchangeable sodium percentage
ET	Evapotranspiration
FI	Furrow irrigation
GW	Ground water
IGP	Indo-Gangetic Plains
IW	Irrigation water
LR	Leaching requirement
MB	Mungbean
MW	Maize-wheat
NTF	No-till flat
NW	North-west
PAU	Punjab Agricultural University
PAWC	Plant-Available Water Capacity
PB	Permanent Bed
PBB	Permanent broad bed
PI	Precise irrigation
PNB	Permanent narrow bed
PRB	Permanent raised beds
PRD	Partial root-zone drying
PTR	Puddled transplanted rice

+R	Residue retention
−R	Residue removal
RSC	Residual sodium carbonate
RW	rice-wheat
SA	South Asia
SAR	Sodium adsorption ratio
SDD	Stress degree days
SDI	Surface drip irrigation
SMP	Soil matric potential
SSDI	Sub-surface drip irrigation
SW	Sodic water
TDR	Time-Domain Reflectometer
WP	Water productivity
WP_{ET}	Evapotranspiration based water productivity
WUE	Water use efficiency
ZT	Zero-tillage

15.1 Introduction

Water is the most significant source for the sustainable development of any nation. Agriculture withdraws about 70% of water in India. There are demands for redirecting water from farming to other segments. In any case, re-allocation of water out of farming can have a sensational effect on worldwide nourishment markets. It is estimated that water availability in India for farming use may be condensed by 21% by 2020, ensuing yield decline, thus rise in price, and food crisis. Thus, food security in present times and future will depend on the ability to enhancing production with dwindling irrigation water availability for growing crops. It is widely known that the application of irrigation maintains adequate soil moisture supply throughout the growing period and results in higher crop yields (Lobell et al. 2009) to achieve Govt. of India's mission *more crop per drop* (Fig. 15.1). It enables major production reactions by using excellent yielding varieties, nutrients, crop establishment methods, etc. India has about 140 million ha of cultivable land and 54% of the net sown area is dependent on rain (Dhawan 2017). About 60% of food production is accounted for by irrigated agriculture in India. The Indian population is expected to reach 1.6 billion by 2050, ensuing in more need of food, water, energy, and shelter. This needs to expand or improve the water resources in India. The world's population by 2050 will reach 9.15 billion from the current level of 7.79 billion wherein the South Asian population will be a major constituent (24.5%) with the Indian population constituting 17.9% (Table 15.1). Wheat, maize, and rice, and to some extent, millets and sorghum are major food articles crucial to the survival of millions of people around the world. The South Asian region is one of the world's key breadbaskets, producing almost 20%

Fig. 15.1 Goal of Modern Agriculture ‘More Crops per Drop’

and 31% of the world’s wheat and rice, respectively, which are the main constituents of diet of the majority of the population. The International Food Policy Research Institute’s report (IFPRI 2019) indicates that the total cereal production in the world and South Asia in 2050 will increase by 50.1% and 62.7%, respectively, over the 2010 level under the no-climate change scenario. Whereas under the climate change scenario, it will be increased by 38.7% and 48.4%, respectively indicating serious implications of climate change effects on cereal production and food security (Table 15.2). Moreover, the global water demand is estimated to rise from 3500 to 5425 km^3 between 2000 and 2050. There is an indication that climate change affects food production and water sources with more degree of unpredictability and paucity at regional scale (Lacombe et al. 2019; Kumar et a. 2018). Meeting this unsurprising condition is doubly challenging allowing for 94% of the land suitable for agriculture is already in production and 58% of area under agriculture faces numerous climatic vulnerabilities of water scarcity and tremendous heat stress (Amarnath et al. 2017).

In India, per capita, water accessibility is lesser than the globe’s normal, and in Indus Basin, it is very demanding (Babel and Wahid 2008; Kumar et al. 2021). Fischer et al. (2007) reported an increase of 50% and 16% in irrigation water (IW) requirements between 2000 and 2080 in developing regions and developed regions of the world, respectively. Global climate change increases greenhouse gases which further affected the rainfall pattern. For example, the rainfall pattern changes with less and erratic rain over the last 40 years in the north-west (NW) India (Prabhjyot-Kaur et al. 2013; Narjary et al. 2014).

The ground water investigations show that 32% to 84% of poor-quality water is used in India. The ground water of arid and semi-arid regions is saline and sodic, respectively. The arid and semi-arid states of India viz. Rajasthan, Haryana, and Punjab have 84%, 66%, and 42% of poor-quality ground waters, respectively

Table 15.1 Population trends and projections in world, South Asia, and India over a century

Population	1950	1960	1970	1980	1990	2000	2010	2015	2020	2030	2050
World population (billion)	2.54	3.03	3.70	4.46	5.33	6.14	6.96	7.38	7.79	8.31	9.15
South Asia population (billion)	0.48	0.57	0.71	0.90	1.13	1.39	1.64	1.75	1.86	2.02	2.24
India population (billion)	0.38	0.45	0.56	0.70	0.87	1.06	1.23	1.31	1.38	1.50	1.64
Share of India in world population (%)	14.84	14.85	15.00	15.68	16.39	17.20	17.74	17.75	17.70	18.10	17.91
Share of South Asia in world population (%)	18.78	18.87	19.29	20.20	21.28	22.64	23.56	23.70	23.82	24.26	24.50

Source: UN (2019), World Population Prospects 2019, https://population.un.org/wpp/

Table 15.2 Projections of cereal production and consumption in the world and South Asia with and without climate change scenario

	Total cereal production (million tons)					Per capita food consumption (kg per capita per year)				
		Without climate change		With climate change			Without climate change		With climate change	
	2010	2030	2050	2030	2050	2010	2030	2050	2030	2050
World	2155	2746	3235	2622	2989	143.5	146.7	148.3	143.4	140.4
South Asia	279	384	454	362	414	148.5	150.7	154.1	147.5	145.9
Production in South Asia as % of world	12.95	13.98	14.03	13.81	13.85	–	-	-	-	-

Source: IFPRI (2019)

(Minhas and Gupta 1992; Sharma et al. 2010). This poor-quality water further deteriorates soil fertility and crop productivity. Nevertheless, if properly managed, this water can be used to increase crop and irrigation water productivity.

At present in South Asia (SA), there is a need to enhance water productivity (WP) due to both physical and economical water scarcity. In irrigated RW of IGP of India, more water input coupled with low irrigation water productivity resulted in the depletion of ground water. There is a need to increase the productivity of wheat-based cropping systems to meet food demands in the coming future. Rice is water-guzzling crop and needs huge amounts of water (2500 L) for 1 kg production (Bouman 2009) and water losses are more in the form of evapotranspiration (ET) and soil percolation (Kukal and Aggarwal 2002; Bouman 2009).

To sustain food security and water resources in the world, there is a need to improve the crop WP (Brauman et al. 2013; Kumar et al. 2021). In NW Indo-Gangetic plains (IGP), water management was an important factor in ushering the *Green Revolution*. In north-western parts of India, Rice-wheat (RW) played important role in food security in NW India. But due to serious groundwater depletion, its future is under threat (Hira 2009). Hence, the need of the hour for efficient water management with low cost and environment-friendly methods. The WP could be enhanced either by increasing production with the same water amount or the same production by using a low water amount. With irrigation scheduling and proper agronomic practices, water could be saved thus enhancing WP. However, WP in rainfed agriculture can be enhanced by groundwater storage and recharging. There is a need to implement strategies to save water and increasing WP in agriculture. A meta-analysis of global crop water productivity of three world-leading crops (wheat, corn, and rice) was done by Foley et al. (2020) and reported to improve water productivity of crops in the highest water use for water-saving areas. Researchers (Ali and Talukder 2008; Humphreys et al. 2010; Yadvinder-Singh et al. 2014) discussed different strategies to enhance WP, the major focal point of this chapter is to amalgamate novel findings for efficient water management under CA-based management systems.

15.2 Water Resources of South Asia

Sustainably increasing agricultural production to meet the growing demand for food, especially under a growing scarcity of water, is a major challenge under the constantly changing climate. South Asia though home to nearly 25% of the global population contains very less (~4.6%) global annual renewable water assets (FAO 2016; Lacombe et al. 2019;). The agriculture section in South Asia consumes more than 90% of water compared to 70% worldwide. The average water availability in South Asia is low (1137 m^3/person/year) which varies widely among different South Asian countries (Lacombe et al. 2019) with the least availability in Pakistan (1306) and India (1458), the two major cereal producing countries of the region (Table 15.3). India, South Asia’s large geography inhabiting over 72% of the region’s population has 2.4% of the world’s total geographical area and 18% of

Table 15.3 Water resources in South Asian countries

	Afghanistan	Bangladesh	Bhutan	India	Nepal	Pakistan	Sri Lanka	South Asia
Rainfall/snowfall (km^3/year)	213	396	84	3560	225	393	112	4980
Internal renewable water resources (km^3/year)	47	105	78	1446	198	55	53	1982
Surface water (km^3/year)	10	1122	0	635	12	265	0	–
Ground water (km^3/year)	10	25	7	363	19	47	7	–
Total renewable water resources (km^3/year)	65	1227	78	1911	210	247	53	–
Per capita availability of total renewable water (m^3/person/year)	2008	7622	100,645	1458	7372	1306	2549	1137
Agricultural water uses as % of total water use	98	88	94	90	98	94	87	91

Source: Adapted from Lacombe et al. 2019; FAO 2016; http://data.worldbank.org the world's population but only 4% of its fresh water resources. Annual water availability in India was about 3000 cubic meters (m$^{3)}$ per capita in 1951 which has declined to 1458 m^3 per capita due to an increase in population and enhanced water use in other sectors of the economy. As per the Falkenmark Index which is a commonly used indicator of water scarcity, a country with renewable water availability below 1700 m^3 per capita per annum is categorized as water-stressed. Although this index cannot be directly applied to the whole South Asian region due to variations in lifestyle and water usage as compared to developed nations. Nevertheless, the region with per capita total renewable water availability of 1137 m^3/year is by and large a water-stressed region and the declining per capita availability calls for greater restraint in water use management technologies. The agricultural water use as a percentage of the total water use in south Asian countries varies from 90-98% with a regional average of 91% (Table 15.3) and hence need high attention and greater efforts for developing precision water management technologies and practices to reduce the agricultural water use by enhancing water use efficiency.

The major issues related to the variability in available water resources in the region are (a) large temporal variability leading to disasters such as floods and droughts; (b) high regional mismatch between availability and rapidly increasing demand for various uses while availability remains nearly the same; and (c) unsustainable use of both surface and ground water resources to meet the growing demand. High temporal variability in South Asia is largely due to the monsoon climate where about 70% of the annual rainfall takes place in a limited span of 4 months, i.e., from June to October. Consequently, in this period, the rivers carry about 70–75% of their annual flows, at times much beyond their capacity to safely carry such huge volumes of water. During the remaining period of eight–months, river flows account for the residual 25–30 percent and many rivers run dry during summer months. Groundwater levels also follow a somewhat similar pattern of rising and fall, but with some staggered delay. Large variability in water availability gives rise to a host of problems, including floods and droughts. In addition, there are large spatial variations in water availability that leads to scarcity in some regions and surpluses in other river basins, normally occurring at the same time.

The population is the key determinant in increasing demand for cereals. To meet the increasing demands for water, progressively increasing quantities of surface and sub-surface water is being used. Although India has been largely dependent on groundwater for drinking water supply and for producing the required quantity of cereals, yet due to its unsustainable withdrawal of ground water in many places, water tables are depleting resulting in drying of wells, increasing pumping cost, decreasing base flows in rivers, and pollution of water (Humphreys et al. 2010; Meena et al. 2020). Rather than looking at surface and groundwater separately, it is necessary to manage the water resources conjunctively to tide over the water crisis. Policy objectives should aim at the conservation of water, reduction in demands, and efficient and rational water transfer across geographies. All options to check water demand should be examined, especially in water-scarce regions. The agriculture sector which accounts for more than 80% of the total water demand in the country, provides a huge opportunity for optimize the use of water. It is estimated that water use efficiency in agriculture is about 40% in the case of surface and about 50% for groundwater use and there is a huge scope for its improvement. The current water use for irrigation in the country being 550–600 BCM, an increase of about 20% in water use efficiency can save enough water to significantly bridge the water availability and demand gap in other sectors. Farmers need to be incentivized for the adoption of different water-saving technologies to improve water productivity (more crops per drop) for the development of sustainable cereal production systems in the country.

15.3 Water Application Efficiency and Water Productivity: Concepts, Definitions, Measurements

15.3.1 Water Productivity Concepts and Definitions

The different scientists defined WP in different ways depending on the individual use for which it was determined. The idea of WP- defined as an increase in yield (product) per unit of water consumed- is regarded as ever more important. To dodge these disarrays in the future, it was recommended that the term WP for crop production should be defined in terms of yield or biomass/ET (either in kg m^{-3} or kg kg^{-1}). Among crop physiologists, the WP of crop encompasses a long convention which they proceed to call water use efficiency (WUE) (Bluemling et al. 2007; Perry 2007; Yadav et al. 2020). The term WP is said to be maximizing the production per unit of water availability in times of restricted water resources and increasing food demand (De-Fraiture and Wichelns 2010; Molden et al. 2010).

15.3.2 Water Productivity Measurement

To calculate the WP or WUE, there is a need for the minimum data set viz. an amount of irrigation and rainfall, soil moisture content before sowing and after harvesting, runoff, deep drainage beyond the root zone for the whole cropping system including the intervening periods. Estimation of ET involves crop modeling (Ahmad et al. 2002; Belder et al. 2005; Jehangir et al. 2006) or the water balance components (Prihar et al. 1974, 1976; Choudhury et al., 2006). The problem in measuring exact deep percolation and runoff may lead to overestimations of ET (Oktem et al. 2003; Sun et al. 2006). Nevertheless, there might be a need to consider upward capillary movement from groundwater into the root zone. Taking into account the soil spatial inconsistency and land properties, crop growth pattern, modeling studies of the soil water balance parameters will positively enhance the WP under water scarcity situation.

15.4 Approaches for Higher Water Productivity

15.4.1 Establishment Techniques

This approach is based on the different establishment methods. Different approaches for optimizing WP include the smart seeding method in rice, zero-till in wheat, rice residue retention, and raised bed planting.

15.4.1.1 Smart Seeding Method in Rice

Rice, as a flooded crop, is the foremost and obvious target for water conservation because it consumes a lot of water. Direct seeded rice (DSR) could be a viable option to decrease the water inputs in rice (Kukal et al. 2014; Singh et al. 2015). Main driving force behind DSR is economic water use. Studies showed yields to vary from 4.5 to 6.5 t ha^{-1}, which is about 20–30% lower than that of lowland varieties grown under flooded conditions (Kumar and Ladha 2011). However, they further reported lower water use and higher WP and net returns than that of lowland rice. In other studies, water-saving of 25–30% in DSR compared to flooded transplanted rice was reported in NW India under silty loam soils (Kamboj et al. 2012; Gathala et al. 2014). A two-year field experiment in the IGP of India showed that water use and economic profitability and the yields of rice in the conventional puddled transplanted rice (PTR) and zero-till (ZT) DSR on flat bed systems were equal (Bhushan et al. 2007). Using 'Lucky seed Drill, DSR could also be sown when it comes to *tar-wattar* condition with two cultivations (with cultivator) followed by two planking (PAU 2021).

15.4.1.2 Zero-Tillage in Wheat

Elements of CA began to be introduced in RW systems of the IGP in the late 1990s, starting with ZT wheat sown after rice (Erenstein and Laxmi 2008). ZT wheat is widely accepted with an area around 5 M ha in IGP, but acceptance of permanent ZT systems is marginal (Erenstein and Laxmi 2008). Studies (Hobbs and Gupta 2003; Humphreys et al. 2005) showed IW savings (15–30%) under ZT wheat compared to conventional till (CT) wheat in the RW system in India. The residual soil moisture from rice crop saves pre-irrigation amount to wheat crop and reduces IW by ~10 cm in ZT wheat (Malik et al. 2002).

15.4.1.3 Surface Mulching/Residue Retention

Soil evaporation (Es) is the process in which water in the soil changes to water vapor (vaporization) and escapes to the atmosphere. Evaporation from the soil surface or water ponding on the soil surface is a major source of water loss in both rice and wheat crops. Across a wide range of environments and cultural practices, the Es/ET ratio in rice and wheat ranged from 30 to 56%. Suppression of Es generally results in higher soil water content in the short to medium term. In Punjab, Balwinder-Singh et al. (2011a) reported decreasing ET by reducing Es with rice straw. Studies (Verhulst et al. 2012; Sidhu et al. 2015) reported an increase in soil water content under ZT systems in wheat mulching with rice straw.

15.4.1.4 Raised Bed Planting

This work was initiated by Sayre and Hobbs (2004) in RW system after the success of maize–wheat system in Mexico. Researchers (Dhillon et al. 2000; Ram et al. 2011) reported similar or higher wheat grain yield and decreased (30-40%) irrigation amount on raised beds compared to conventional flat sown wheat. Jat et al. (2015) recorded 24.5% higher WP in MW system because of less irrigation water applied in maize and wheat under permanent raised beds (PRBs) than ZT flat. This is apparent from the low amount of irrigation water with high system yield in PRBs compared with ZT flat. Similar results of lower water use and higher WP of maize on PRBs were also reported by Jat et al. (2013). On a system basis, PRBs saved 29.2% irrigation water compared with no-till flat (NTF). However, this practice is not popular due to the lack of machinery for sowing the crops.

15.4.2 Irrigation Scheduling Approaches

This approach determines the timing and amount of water application to crop. This approach is based on "soil water balance" in which soil moisture storage changes with time is the difference between water input (irrigation + rain) and the losses in the form of drainage, runoff, and ET. It involves the irrigation timing and given irrigation amount. Different approaches for optimizing the irrigation timing includes key crop growth stages, soil moisture diminution approach (water content of soil or soil matric potential), atmospheric evaporativity, and IW application at varied cumulative pan evaporation (CPE).

15.4.2.1 Climate-Based Approaches

Climate-based approaches to irrigation scheduling involve the use of a measure of cumulative potential evaporation (Allen et al. 1998). Potential evaporation is determined in a range of ways including pan evaporation, and reference ET calculated from meteorological data in a variety of ways but the modified Penman–Monteith method is generally preferred. Crop ET is then calculated from potential ET using crop factors. Irrigation is scheduled after a pre-determined amount of ET has occurred, and this threshold amount varies with soil type (plant-available water capacity, PAWC), crop type (e.g., shallow versus deep-rooted crops), and stage of crop growth. The threshold is determined using information from past studies on crop water use.

15.4.2.2 Evaporativity-Based Approach

As per this approach, the concept of IW application is when soil profile moisture gets depleted to such a level that crop growth may get affected. Prihar et al. (1974) recommended a concept to irrigation scheduling on the ratio of the fixed depth of IW to CPE since preceding irrigation (open pan evaporation (Pan E) minus amount of rain) for the wheat crop. The amount of irrigation water is calculated on the basis of acceptable depletion of water in soil profile (Prihar et al. 1978). This deficit irrigation (DI) practice supports the utilization of profile stored soil water by encouraging deep roots in crops. This method saves 2 out of 6 irrigations in wheat at various growth stages without affecting crop grain yield (Prihar et al. 1976).

The alternating irrigation at two-day interval after vanishing of flooded water from the soil surface helps in increasing rice grain yield (Sandhu et al. 1980) which saves irrigation water. The last irrigation timing (2 weeks before rice harvesting) also saves IW without any yield penality (Sandhu et al. 1982).

15.4.2.3 Soil-Based Approach

Soil-based irrigation scheduling is based on a determination of soil water status (volumetric soil water content or matric potential) within the root zone, and knowledge of the critical threshold for irrigation. When based on volumetric soil water content, the threshold for irrigation is generally expressed as percentage depletion from the total plant-available soil water holding capacity (PAWC, the amount of water held in the soil water between field capacity and permanent wilting point) of the root zone. For example, a common recommendation is to irrigate when the soil water content of the root zone decreases to 50% of PAWC, then apply enough water to replenish the deficit. This method can be used to calculate both when and how much to irrigate. In practice, rate of soil drying or water extraction from soil profile with time is good indicator for irrigation timing. A range of techniques can be used to determine volumetric soil water content, include neutron attenuation, time-domain reflectometry (TDR), and capacitance (Charlesworth 2005). Method which allows frequent determinations of soil water content and logging of the data (at least daily, preferably more often) is most useful for this because collecting frequent data as well as soil sampling is not practical.

In the second approach, irrigation is scheduled according to soil matric potential (SMP), usually at a particular soil depth. Soil matric potential is directly related to the energy required by the crop to extract water from the profile. The most common methods of determining SMP are manually read tensiometer and granular matrix sensors which may be read manually or logged. Modern tube tensiometers are relatively cheap, robust, and easy to use, and are a simple hydrostatic system consisting of a porous ceramic cup connected to a plastic tube that is connected to a vacuum gauge. Tensiometer measure in situ moisture in real-time, and are accurate to SMP from a range of 0 to about −80 kPa and thus cover the entire range needed for most crops. In present times, the SMP-based irrigation scheduling is the most suitable technique.

Rice is a very water-sensitive crop and there is a yield penalty once the SMP decreases beyond −10 kPa at 15 cm soil depth (Bouman and Tuong 2001). For puddled transplanted rice (PTR), Kukal et al. (2005) reported irrigation scheduling based at −16 kPa at 20 cm soil depth. Under different tillage and mulch treatments, Gupta et al. (2016) reported SMP (mean of 3 replicates) of that treatment decreased to −35 kPa at 32.5 cm soil depth and − 15 kPa at 17.5 cm soil depth in wheat and dry seeded rice, respectively.

With an increase of SMP from −20 to −40 to −70 kPa, there was a yield decline in both PTR and DSR on a clay loam soil with having seasonal rain ~600-800 mm (Sudhir-Yadav et al. 2011). On sandy loam soil, Mahajan et al. (2012) reported no difference in DSR grain yield when irrigation scheduled at −10 and − 20 kPa. However, Ghosh and Singh (2010) reported no difference in grain yield when irrigation was scheduled at different SMP (0, −20, and − 40 kPa) but observed a significant yield decline at −60 kPa. For eastern Indian conditions, they suggested SMP of −40 kPa for obtaining the highest grain yield and WP in DSR. On the basis of SMP, Kukal et al. (2009) developed a cheap and farmer-friendly PAU tensiometer (color coding) for rice crop, which make use of colored tapes for the simplicity of the farmers. The farmers were told to install the tensiometers at 20 cm depth and irrigate the rice crop when the water inside the tensiometer tube crosses the green mark and enters the yellow mark. A very simple and cheaper version of the tensiometer has recently been developed for rice farmers (the PAU tensiometer, PAU 2010).

15.4.2.4 Plant-Based Approach

Plant-based irrigation scheduling is based on the physiological and phenological conditions of the crop. The physiological condition (water stress level) can be judged from canopy temperature depression relative to air temperature (measured by infrared thermometry), and then the calculation of cumulative the stress degree days (SDD) (Idso et al. 1981) and crop water stress index (Jackson et al. 1988) used for irrigation scheduling. Phenological stages can also be used to determine when to irrigate. In wheat, critical growth stages for irrigation are crown root initiation (CRI), tillering, jointing, flowering, and grain filling stages. Water stress at any of these stages may result in loss of yield depending upon the severity of the stress.

Das et al. (1985) described that the difference between canopy (Tc) and air temperature (Ta) was lower in unstressed treatments compared with stressed conditions in wheat. Working on sandy loam soil, Buttar et al. (2005) reported a 55% of deviation in grain yield of wheat and this index is helpful to schedule irrigation on the basis of crop water status. Similar were the findings of Gontia and Tiwari (2008) in central India. However, this is a very costly technique and not economically viable for small holding farmers. Moreover, the irrigation methodology requires good knowledge of the physiology of crops and its sensitive stages of crop growth (Zhang et al. 1999).

15.4.2.5 Deficit Irrigation (DI) Approach

It is an irrigation water-saving approach in which IW is given at a low quantity compared to total water requirements of the crop (i.e., ET) to increase WUE. The amount of irrigation varies between 60% and 100% of ET. However, water-saving and associated higher WP depends upon the crop cultivar, sowing time, soil texture, and location characteristics which predict whether there is yield penality or not under the DI approach (Ahmadi et al. 2010b). The water-sensitive stage differs in different crops so there is a need to design DI program accordingly to avoid any yield loss. However, such information is very scarce.

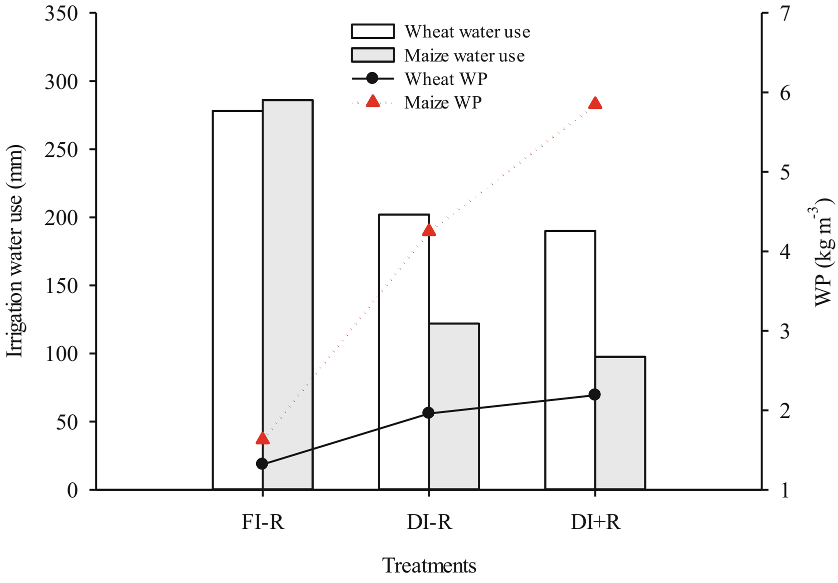
In DI, water is applied to crop at sensitive growth stages to increase water productivity and minimize yield loss (Fereres and Soriano 2007). Ali et al. (2007) identified two critical stages viz. crown root initiation (CRI) and booting to heading in wheat and urged to avoid drought stresses at these two stages. When applied irrigation is less than ET, water is taken from the soil profile by the crop to recompense the shortage.

Research (Soundharajan and Sudheer 2009) indicates that DI enhances WP of cereal crops viz. wheat, maize, and rice by 10–42%. The field studies in India reported that with two supplemental irrigations, WP of maize, groundnut, sunflower, wheat, and potato was 0.55, 0.22, 0.23, 0.41, and 2.27 kg m^{-3}, resulted in WP enhancement by 40, 14, 22, 38 and 7%, respectively when three irrigations were applied (Kar et al. 2004). Ali and Talukder (2008) reported that DI plus conservation agriculture techniques (mulching) enhance the yield and WP. In China, Zhou et al. (2011) reported that the combination of ridge furrow planting and DI approach increases WP of both maize and wheat crops as compared to flood irrigation in conventional systems. Partial root-zone drying (PRD) is another form of DI that enhances WP while maintaining crop yield (Ahmadi et al. 2010a). Sepaskhah and Ahmadi (2010) compared the DI approach with PRD and reported that PRD is doing well as an alternative irrigation technique and saves ~50% IW without any yield loss as compared to full irrigation. Another option of PRD is irrigating each furrow or alternately and Grimes et al. (1968) reported alternate furrow irrigation is the best water-saving technique. A field study conducted at BISA Ladhowal (Punjab, India) showed that alternate furrow irrigation maintained yields of spring maize to that of irrigated every furrow but with a 50% reduction in the amount of IW (H.S. Sidhu, Personal Communication).

15.4.3 Drip Irrigation System

In the areas of water paucity, drip irrigation could be a viable option in water-saving and ultimately increasing the area under irrigation to enhance crop yield and water productivity. However, the flood irrigation method is the traditional practice followed by farmers. Major portion of this flood irrigated water is considered as a deep drainage factor, which is being considered as an energy-driven process in case groundwater is the irrigation source. Water logging and salinization may result in canal command areas. However, drip irrigation system is considered to be the best possible option to overcome these problems. Drip irrigation (surface and sub-surface) has higher water efficiency than the conventional system (flood) with more conveyance efficiency (Narayanamoorthy 2006). These irrigation systems enhancing WP reduces deep drainage, and decreases soil evaporation losses (Camp 1998).

Researchers have detailed considerable progress in crop yield and WP under drip irrigation system compared with the conventional irrigation (flood) in different crops viz. cotton, sugarcane, soybean, maize, and wheat (Aujla et al. 2007). Sharda et al. (2017) reported an increase in rice grain yield and water-saving under surface drip irrigation compared to flood irrigation with higher Wpi under surface drip irrigation. Beecher et al. (2006) conducted an experiment in Australia and reported a decrease in rice yield and no improvement in WP by using drip irrigation. In Egypt, Abd El-Waheda and Ali (2013) observed higher grain yield in maize under drip irrigation



Furrow irrigation-residue removed (FI-R); Drip irrigation-residue removed (DI-R); Drip irrigation-residue retained (maize 50% upper+wheat 25% lower) (DI + R)

Fig. 15.2 Effect of irrigation method and residue on water productivity (WP) of wheat and maize in wheat–maize system (data pooled over 2 years). (Sandhu et al. 2019)

compared with sprinkler irrigation systems. Drip irrigation helps both in enhancing grain yield and saves water (Tiwari et al. 2003). Sharma et al. (2009) reported that the drip irrigation system has the potential to decrease irrigation amount (43.96 billion cubic meters) in five crops (groundnut, sugarcane, onion, cotton, and potato) of India.

Further, efforts have been made to reduce the cost of drip irrigation systems by reducing the primary cost on drip tape and emitters. Veeraputhiran and Kandasamy (1999) reported higher cotton yield (11.6–20.4%) and WP (31.4–53.1%) under drip irrigation systems compared to flood irrigation. Patil et al. (2004) reported no difference in cotton yield and WP by using drip irrigation system and alternate furrow irrigation but considerably higher as compared with flood irrigation.

With increasing implementation of the CA techniques, surface drip irrigation (SDI) and sub-surface drip irrigation (SSDI) gives an excellent chance for harmonizing water-saving profits. Sandhu et al. (2019) reported irrigation saving (88 mm and 168 mm) and more WP (66% and 259%) in wheat and maize crops, respectively on permanent beds using SDI with residue retention in India (Fig. 15.2). However, Sidhu et al. (2019) compared different combinations of lateral spacing and depth of SDI and SSDI with conventional till flood and zero-till flood in rice–wheat system at CIMMYT-BISA Ludhiana, Punjab. Under SSDI accompanied with CA, they reported irrigation water savings of 48–53% and 42–53% in rice and wheat,

Table 15.4 Effect of residue mulch, and drip spacing and flood irrigation system on irrigation amount (mm) in rice and wheat seasons (Sidhu et al. 2019)

	Rice 2014	Rice 2015	Wheat 2014–15	Wheat 2015–16
Treatments	Irrigation amount (mm)			
T1	592	555	169	149
T2	606	601	197	198
T3	583	577	167	151
T4	563	561	169	159
T5	646	614	200	189
T6	627	580	165	167
T7	1072	1010	298	403
T8	1296	1109	306	356

T1: ZTRW+R + $SDI_{33.75}$ (zero-till rice-wheat with residue; surface drip irrigation, laterals spaced at 33.75); T2: ZTRW-R + $SSDI_{33.75\text{-}15}$ (zero-till rice-wheat without residue, sub-surface drip irrigation, laterals spaced at 33.75 at 15 cm depth); T3: ZTRW+R + $SSDI_{33.75\text{-}15;}$ T4: ZTRW +R + $SSDI_{33.75\text{-}20}$ (sub-surface drip irrigation, laterals spaced at 33.75 at 20 cm depth); T5: ZTRW-R + $SSDI_{67.5\text{-}15}$ (sub-surface drip irrigation, laterals spaced at 67.5 at 15 cm depth); T6: ZTRW+R + $SSDI_{67.5\text{-}15;}$ T7: ZTRW+R + FL (zero-till flood with residue); T8: CTRW-R + FL (conventional till flood without residue)

respectively, (Table 15.4) compared to conventional irrigation (flood) systems. They further reported higher WP under SSDI compared with flood treatments in both rice and wheat crops. Similar findings were also reported in maize–wheat system experiment at CIMMYT-BISA Ludhiana (Punjab) with SSDI (M.L. Jat, Personal Communication). Jat et al. (2019) conducted an experiment on RW and MW cropping systems in CA (SSDI) and convention flood irrigation system. They reported the saving of irrigation water and higher WP under CA (SSDI) as compared to the convention system in both RW and MW cropping systems. They further reported that substitution of rice with maize (maize–wheat–mungbean SSDI system) saved 84.5% of irrigation water with 19.7% higher productivity. The existing studies have employed wireless sensors for monitoring the soil condition for irrigation. However, there are no reports showing linkage of The Internet of Things (IoT)-based devices with SSDI for automated irrigation for cereal crops.

15.5 Conservation Agriculture for Increasing Water Use Efficiency

The CA benefits are chiefly linked with its favorable ecological and soil effects in contrast to conventional systems, which include improvement in physical fertility of soil and water use efficiency (Hobbs et al. 2008; Farooq et al. 2011; Dhaliwal et al. 2020; Setia et al. 2020). Water conservation as an important element of CA plays an important role in rainfed areas (Rockstrom et al. 2009). Govaerts et al. (2009) working on Mexico soils reported the significance of residue retention of crop in CA improves soil stability and soil water balance components. Major benefits of CA are less soil erosion (water and wind), improved water use efficiency by increased water infiltration rate, nutrient use efficiency, soil organic carbon, soil micro biodiversity, and overall soil health, reduced labor and energy along with timely operations (Hobbs et al. 2008).

In maize–wheat rotation, Ghosh et al. (2015) reported higher (~47%) wheat equivalent yield under CA compared with a conventional system under rainfed conditions of Uttrakhand. Average runoff coefficients and soil loss under CA were lower by ~45 and ~ 54%, respectively, compared to conventional plots. On average, soil moisture storage under CA was higher (108%) compared with conventional plots for wheat crops after the harvest of maize crop. Runoff was maximum in conventional plots. Mean runoff was 39.8% and 21.9% with conventional and CA plots, respectively. After 5-years, average soil loss under conventional and CA plots was 7.2 t ha^{-1} and 3.5 t ha^{-1}. There is an urgent need to run simulation models to study the interactive effect of soil water balance components and crop water input under CA (Scopel et al. 2004).

15.5.1 Crop Water Use and Water Productivity under Conservation Agriculture

Soil evaporation (Es) is considered to be a non-beneficial water loss (Gupta et al. 2021; Jovanovic et al. 2020) and Gupta et al. (2021) reported that Es is a significant loss (600–700 mm) from a ZT dry seeded RW system and the majority (56–66%) of this loss occurred during the rice phase, and 22% and 12–22% during the wheat and fallow phases, respectively. Under different tillage and mulch treatments, Gupta et al. (2019, 2021) reported Es is a significant loss from wheat (127–186 mm) and DSR (358–462 mm) crops. It usually accounts for approximately one-third of crop ET with reasonably little part to crop grain yield. Studies (Balwinder-Singh et al. 2011a; Gupta et al. 2021) reported that mulching of wheat with rice straw decreased Es by 32–48 mm in wheat-growing season. There are many reports of mulch increasing crop water use, yield, and evapotranspiration water productivity ($\mathrm{WP_{ET}}$) under water-limited conditions (Zaman and Choudhari 1995; Acharya et al. 1998).

In some cases, the response to mulch in water-limited situations was also due to higher water uptake from the deeper soil profile due to larger and deeper root system development under mulched conditions (Sharma and Acharya 2000; Rahman et al. 2005). In a 2 years study in rainfed wheat treatment, Chakraborty et al. (2008) found that total water use (ET) was reduced by 79 mm under mulch during the higher and well-distributed rainfall year, and by only 14 mm in a comparatively dry year. Mulch increased $\mathrm{WP_{ET}}$ each year, but by more in the higher rainfall year due to both reduced ET and higher grain yield, while in the low rainfall year the increase in $\mathrm{WP_{ET}}$ was mainly due to higher grain yield. However, in some studies, ET of the mulched crop remained unchanged due to the transfer of water saved from suppressing soil evaporation (Es) used to increase transpiration. Lascano et al. (1994) found that wheat straw mulch reduced Es from a cotton crop by 38%, but that transpiration was increased by the same amount, resulting in no decrease in total ET.

There are few reports on the effect of mulch on WP_{ET} of fully irrigated wheat, and on whether mulch reduces the need for irrigation. In Punjab, India, Yadvinder-Singh et al. (2008) found that mulch delayed irrigation by 1–3 weeks when irrigations were scheduled based on SMP, but it did not affect the total number of irrigations.

A number of other studies reported a significant increase in wheat grain yield with residue compared to no residue (Chakraborty et al. 2008, 2010; Yadvinder-Singh and Sidhu 2014). Chakraborty et al. (2010) reported that rice residue retention increased mean wheat grain yield (17.1%), decreased crop water use (3–5%), and increased WUE (38.3%) compared with no rice residue retention.

Rice residue retention decreases irrigation requirements in wheat by lowering soil evaporation (OFWM 2002). Using the criteria of irrigation scheduling at key growth stages, Ram et al. (2013) reported irrigation saving of 75 mm in mulched wheat (3 irrigations) as compared to non-mulched wheat (4 irrigations) with no difference in wheat grain yield in both management scenarios in Punjab, India. The effect of mulch in reducing irrigation requirement is well known (Sidhu et al. 2015; NAAS 2017), however, its effects on other components of the water balance are less adequately studied.

Under different tillage and mulch conditions in the wheat, the irrigation number varies with seasonal rainfall patterns and irrigation timing (Gupta et al. 2016). For example, in the RW system in NW India, mulching of wheat with rice straw decreases irrigation necessity in some years, but not in others (Yadvinder-Singh et al. 2008; Balwinder-Singh et al. 2011b; Gupta et al. 2016). The simulations study conducted by Balwinder-Singh et al. (2016) reported that mulching of wheat could save 1-irrigation (50 mm) in ~50% of years. These results are consistent with findings of Balwinder-Singh et al. (2011b) and Gupta et al. (2016) who explained that irrigation is reduced by one and occasionally it does not (Yadvinder-Singh et al. 2008; Gupta et al. 2016) due to rice residue retention and soil water. Gupta et al. (2016) reported that mulching of wheat with rice residue reduced irrigation necessity in wheat in some years, but it has no residual effect in succeeding DSR crops. On SMP-based irrigation scheduling in wheat, Balwinder-Singh et al. (2011b) reported saving of 75 mm in mulched wheat compared with non-mulched wheat. These preliminary findings advocate the separate SMP-based irrigation scheduling in mulched wheat for less IW requirement.

15.5.2 Effect of Conservation Agriculture Practices on Water Use Efficiency in Major Cereal-Based Systems

15.5.2.1 Rice–Wheat System

Choudhary et al. (2018) compared conventional till rice–wheat–mungbean (CTRW + MB), zero-till rice-wheat along with residue retention and precise irrigation (ZTRW + R + PI) and ZTRW + MB + R + PI in a CA-based RW system. During the 3-years of study, they reported higher water consumption in conventional PTR compared with the other treatments. Using the SMP approach, water input was less (23–32%) in zero-till DSR compared to PTR. The system productivity and total (irrigation + rainfall) WP (3-year avg.) was higher by 24% and 41% in ZTRW +MB + R + PI compared with CTRW, respectively. Kumar et al. (2018) compared the four scenarios viz., conventional rice–wheat–fallow system in Scenario 1, the reduced till rice–wheat–mungbean system in Scenario 2, full CA-based rice–wheat–mungbean system in Scenario 3, and full CA-based maize–wheat–mungbean system in Scenario 4 over the 5-years. They reported the highest water inputs (irrigation + rainfall) in Scenario 1 and lowest in Scenario 4. Compared to the conventional RW–fallow system in Scenario 1, irrigation water savings in Scenario 2 and Scenario 3 were 15% and 28%, respectively. Irrigation input across the years was lower (15–40%) in Scenario 3 compared with Scenario 1. In all the 5 years, WP in Scenario 4 was higher (2.8 to 5.4 times) compared to Scenarios 1 and 2. In direct seeded rice–wheat cropping system over the 3 years, Gupta et al. (2016) reported inconsistent results on grain WP by considering different mulch and tillage combinations. They reported decreased (by 7–14%) grain WP under CT in the first 2 years, and increased it by 9% in the third year, in comparison with ZT wheat. They also reported a significant increase in biomass WP in wheat with residue retention from 6.2 to 8.4 kg m^{-3} and from 5.0 to 6.8 kg m^{-3} in years 1 and 3, respectively.

15.5.2.2 Maize–Wheat and Other Cropping Systems

Direct crop sowing in ZT and permanent bed (PB) plots show the way to maintain favorable soil moisture (Govaerts et al. 2007a, 2007b; Sharma et al. 2011) and improves plant water availability (Jemai et al. 2013) and, as a consequence, it increases crop productivity (Jat et al. 2018a). Water use efficiency could be enhanced with CA-based ZT system (Govaerts et al. 2009). Jat et al. (2018b) evaluated the effects of tillage and crop establishment methods and residue management options on crop yields and water productivity in MW system at Taraori, Karnal (India). The 3-years mean basis system crop productivity and WP under MW system sown on PB and integrated with mungbean (PB + MB) were significantly increased by 28–31% and 37–40.5% compared with CT, respectively. In PB system, crop residues retention lowers losses of evaporation by maintain soil moisture (Jat et al. 2013; Parihar et al. 2016) and saves water (Jat et al. 2015) compared with CT system. Irrigation water moves quickly in-furrow as compared to CT plots in bed planting system and saves water (Jat et al. 2013, 2015). Researchers (Jat et al. 2013; Choudhary et al. 2016; Parihar et al. 2016; Singh et al. 2016) also reported high WUE under the PB system under the same ecologies. Parihar et al. (2016) compared the 4-maize-based systems (maize–wheat–mungbean- MWMb, maize–chickpea–*Sesbania* green manure-MCS, maize–mustard–mungbean—MMuMb and maize–maize–*Sesbania*-MMS) in CA (PB and ZT) and CT for 6 years. The system productivity under PB was higher (8.2–8.5 Mg ha^{-1}) in the initial 2 years and it was maximum (11.3–12.9 Mg ha^{-1}) in ZT plots from the third year. Irrigation water input was lower by 40–65 ha-mm and 60–98 ha-mm in ZT flat and ZT-PB compared with CT, respectively. Choudhary et al. (2018) compared conventional tillage fresh bed MW (FBMW) with CTMW + MB, PBMW + residue (R) + PI, and

Table 15.5 Amount of water applied and water productivity influenced by management scenarios in rice/maize–wheat–mungbean cropping system (Choudhary et al. 2018)

	Irrigation water (mm ha^{-1})			System water productivity (kg grain m^{-3})		
Treatment	2012–13	2013–14	2014–15	2012–13	2013–14	2014–15
CTRW	2508b	1798b	1710b	0.39e	0.47f	0.46 g
CTRW+MB	2671a	1956a	1955a	0.41e	0.50f	0.49 g
ZTRW+R	1828d	1238d	1328d	0.49d	0.63e	0.59f
ZTRW+MB + R	1940c	1348c	1501c	0.53c	0.68d	0.65e
FBMW	662f	435f	405f	0.90b	1.06c	1.07c
FBMW+MB	817e	588e	651e	0.87b	1.03c	1.01d
PBMW+R	402 h	210 h	205 h	1.27a	1.52b	1.57b
PBMW+MB + R	467 g	271 g	273 g	1.29a	1.57a	1.70a

Table 15.6 Impact of CA on irrigation water productivity in maize–wheat system (Das et al. 2018)

	Maize (mean of 2 years)		Wheat (avg. of 2 years)	
Treatments	Irrigation water applied (mm)	Wpi (kg ha^{-1} mm^{-1})	Irrigation water applied (mm)	Wpi (kg ha^{-1} mm^{-1})
CT	531.5a	6.94d	503.0a	9.75bc
PNB	497.0ab	8.09c	443.0b	10.48b
PNB + R	490.0ab	8.65abc	442.5b	11.01ab
PBB	483.0b	9.14b	429.5b	11.09ab
PBB + R	467.0b	10.12a	426.5b	11.60a
ZT + R	505.5ab	9.08b	452.5b	11.28a
ZT	516.0ab	8.43abc	512.5a	9.27c

PBMW + MB + R + PI in a CA-based MW system. They reported lower (87–92%) irrigation in maize under PBMW compared with PTR. They further reported lower irrigation in wheat by 61% and 65% under PBMW compared with FBMW and CTRW. Similar were the trends for system water input and system water productivity (Table 15.5).

In 3 years of study, Parihar et al. (2017) reported higher WUE with PB MWMb system (1.89–2.39 kg ha^{-1} m^{-3}) compared with ZT and CT. In 7 years of experiment, Parihar et al. (2018) observed lower water input (16.8–22.9%) in ZT and PB compared with CT in semi-arid tropics of India.

Das et al. (2014) compared CT, ZT, permanent broad bed (PBB), and permanent narrow bed (PNB) with and without residue (R) under cotton-wheat system and reported water saving of ~3 and 10% in PBB compared with PNB and ZT plots, respectively. Das et al. (2018) reported water saving (62 mm ha^{-1}) and higher (9%) water productivity in maize (Table 15.6).

15.6 Sustainable Management of Poor-Quality Water

Continuous rising demand for water for irrigation especially in water-scarce areas (arid and semi-arid) has necessitated the use of low-quality groundwaters. This irrigation water adds sodium, salts, and harmful elements which further degrade soil and the environment. Sharma and Minhas (2003) explained the quality of irrigation water into different groups (Table 15.7).

15.6.1 Management Options for Saline Water Use

Continuous efforts across different research centers in various regions in India have given different options for the viable use of poor-quality irrigation waters. Different studies have conclusively established that the successful utilization of this water for irrigation can be attained by integrating all agronomic factors judiciously.

(a) Crop Management.

1. Selection of Crops:

   Salinity hinders plant growth because of the low osmotic potential of soil solution which makes it difficult for plants and soil microbes to take up or retain water in their cells thus leading to water deficiency and wilting in plants (Munns and Tester 2008). As a result of more concentration of soluble salts in the soil, the capability of plant roots to take up an ample amount of water for growth and development diminishes (Keren 2000 and Yadav et al. 2011). Therefore, semi-liberal to liberal crops (wheat and cotton) should be preferred and water-guzzling crop-like rice should be avoided for efficient and productive use of saline water.

2. Growth Stages.

   Crops differ in their tolerance level of salinity depending on their growth stages (Rengasamy 2010). In general, saline water use for irrigation purposes should be controlled during the early crop growth phase. Most critical growth

Table 15.7 Classification of poor-quality irrigation water (Sharma and Minhas 2003)

Water quality	EC_{iw} (dS m^{-1})	SAR $(mmol^{-1})^{1/2}$	RSC (meq l^{-1})
A. Good	<2	<10	<2.5
B. Saline			
1. Marginally saline	2-4	<10	<2.5
2. Saline	>4	<10	<2.5
3. High SAR saline	>4	>10	<2.5
C. Alkali water			
1. Marginally alkali	<4	<10	2.5-4.0
2. Alkali	<4	<10	>4
3. Highly alkali	Variable	>10	>4

[a] *EC* electrical conductivity, *RSC* residual sodium carbonate, and *SAR* sodium adsorption ratio

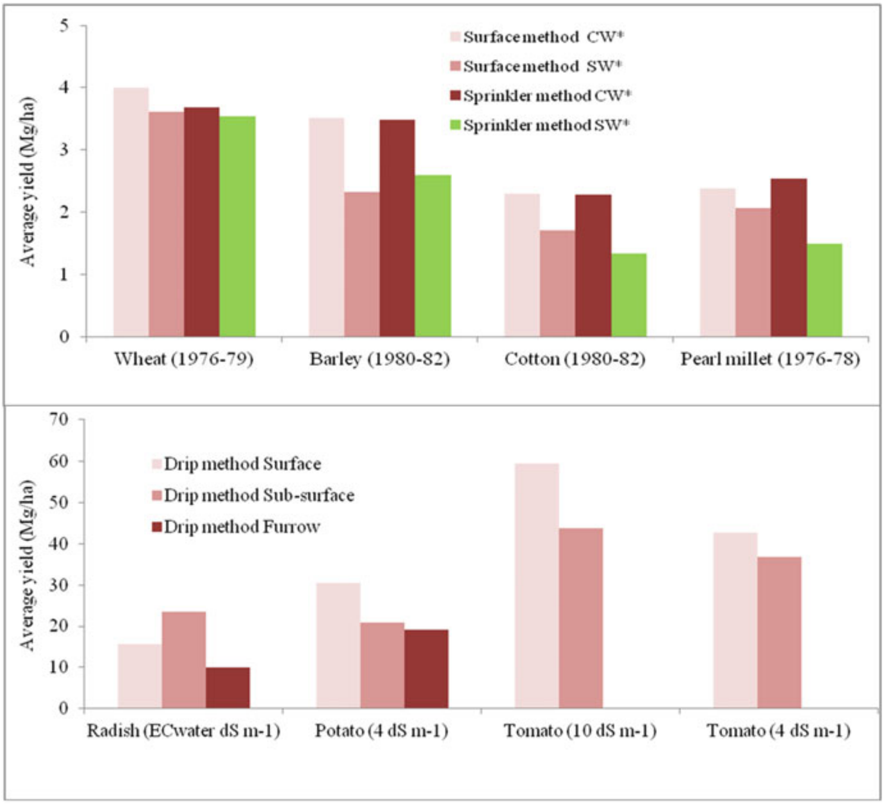
   stages in crops irrigated with poor-quality water are germination, early seedling establishment, and flowering stage.

3. Cropping Sequence.
   Another critical step in reducing the effect of saline environments is the choice of the appropriate cropping sequence. Some recommended cropping sequences that are more remunerative in saline soils are pearl millet–barley, pearl millet-wheat, and pearl millet-mustard. Cotton-based cropping sequences are found to be less remunerative because the yield of the wheat crop that follows the cotton crop is normally truncated due to the late picking of cotton coupled with the time needed for seedbed preparation for wheat (Buttar et al. 2011). Further, mono-cropping is generally recommended in areas with low rainfall (<40 cm/annum) for maintaining salt balances.

(b) Water Management.

1. Irrigation Management and Leaching.
   In absence of any leaching, successive irrigation with saline water causes excessive deposition of salts in the root zone and that results in crop yield decline (Grattan et al. 2015). However, following suggestions with respect to proper irrigation and leaching practices will be helpful in preventing salt deposition in the root vicinity.
   a. Firstly, arid areas would need application of 15–20% more water for irrigation for fulfilling the leaching requirements. The frequency of saline water application for irrigation should be enhanced. Under sub-normal rainfall conditions, salt deposition at the time of the previous rabi cropping period is pressed below the root vicinity preferably through applying heavy pre-sowing irrigation with saline water.
   b. Method of irrigation used largely determines the salt and water pattern in soils. Micro-irrigation systems could be a viable option to utilize poor-quality water mainly for high price crops (Fig. 15.3) (Aggarwal and Khanna 1983; Singh et al. 1978). To keep soluble salt content to lesser levels in seedbeds during germination and application of saline water through sprinklers leads to the better establishment of the crop. On a microscale, an indigenous alternative to drips are pitchers and yet their possibility on field level remains unverified.
   c. Provision of sub-surface drainage in saline waterlogged soils could be helpful to use water from lower depths with proper drainage in rabi crops and therefore lower the necessity for more irrigation water.
2. Conjunctive Use of Canal and Saline Irrigation Water.
   At many places, variable quality water is available at the same location. This situation is common in areas where farmers have limited access to canal water. The mixing of saline and canal water helps to improve the river size and hence increases the irrigation consistency mainly in coarse-textured soils.

   Application of the variable quality waters may be completed separately to diverse fields and crop growing periods, if available on-demand, so as to avoid more salinity water at key crop growth periods. Since the sensitive stages in most crops are germination and seedling establishment, good-quality water must be



*CW- Canal water, SW-Saline water

Fig. 15.3 Crop yield with differential irrigation methods. *CW Canal water, SW Saline water. Source: Aggarwal and Khanna (1983), Singh et al. (1978), AICRP-Agra (2002)

preferentially utilized during the initial stage of crop growth or as pre-sowing irrigation. Thereafter, once the crops attain tolerance to higher salinity, poor-quality water can be applied judiciously. The use of non-saline water at the initial crop growth period is useful for salt-sensitive crops (Minhas and Bajwa 2001; Minhas 2012).

15.6.2 Management Options for Sodic Water Use

Irrigation with sodic water remains a challenge for soil properties and the environment if recommended crop-soil-water management strategies are not followed (Choudhary and Mavi 2019; Minhas et al. 2019). Thus, if problems to support the world food need are to be satisfied, it is imperative that different strategies for sustainable use of sodic groundwaters are followed religiously.

(A) **Land Leveling and Rain Water Conservation.**

Land leveling and establishing of high bunds (30-40 cm) to capture and hold rainwater are basics for the management of the soils with sodic water irrigation. The beating actions expose the soil surface and it could be saved by cultivating the field after the rains. This tradition decreases the water loss through weeds and evaporation but also increases intake of rainwater through the soil.

(B) **Selection of Suitable Crops and Varieties.**

For getting higher crop production and financial returns under variable soil levels of sodium saturation, planting of suitable crops and varieties could play a very major role because of their different tolerance limits to soil sodicity/alkalinity (Ayers and Westcot 1985). Gupta and Abrol (1990) projected the upper permissible limits of exchangeable sodium percentage (ESP) for various crops. The varying ESP levels in soil depend upon the diverse crop development stages (Singh 2017). In general, the performance of the succeeding crop is significantly compromised by crops grown in the preceding season (Tyagi 2003). In a 6-year study, Sharma et al. (2001) reported that the yield of the sorghum-wheat and cotton-wheat was lower compared with the RW cropping system irrigated with sodic water.

Studies by Choudhary et al. (1996a, b) suggested that compared to sensitive ones, the wheat genotype with higher tolerance to poor-quality water had a deep rooting and higher tiller density. A well-known high-yielding wheat variety PBW-343 that produced higher grain yield and quality even with irrigation waters having RSC up to 6.5 me L^{-1} without any significant yield loss (Choudhary et al. 2007, 2012a). Consequently, Choudhary et al. (2012a) suggested that in the sodic water irrigated soils (RSC $>$ 5 me L^{-1}), variety PBW343 should be preferred to obtain suitable yield levels and grain quality than wheat cultivars (PBW550 and PBW502). Furthermore, crops with lesser water requirements should be favored (Minhas and Gupta 1992; Rengasamy 2010). The greater build-up of ESP reduces wheat productivity after rice compared with wheat grown after millet and cotton (Bajwa and Josan 1989a, b, c; Choudhary et al. 2004) under long-term experiment of sodic water irrigation. In addition, wheat cultivar PBW343 response to sodic water (RSC) was controlled by irrigation number and rainfall amount. Crop with more tolerance to soil sodium saturation has been found to keep a low Na/K ratio and more Ca/Na ratio in crops (Bajwa 1982; Choudhary et al. 1996b) by limiting Na absorption (Gill and Qadir 1998). Under ESP of 56.2, Choudhary et al. (2001) reported that seed cotton yield (relative) was 69%, 49%, and 29% in F-846, LD-327, and F-505 cultivar, respectively, as compared with CW. Similarly, Choudhary et al. (2012b) reported that RCH 134 (Bt cotton hybrid) was more tolerable compared with MRC 6301 and MRC 6304.

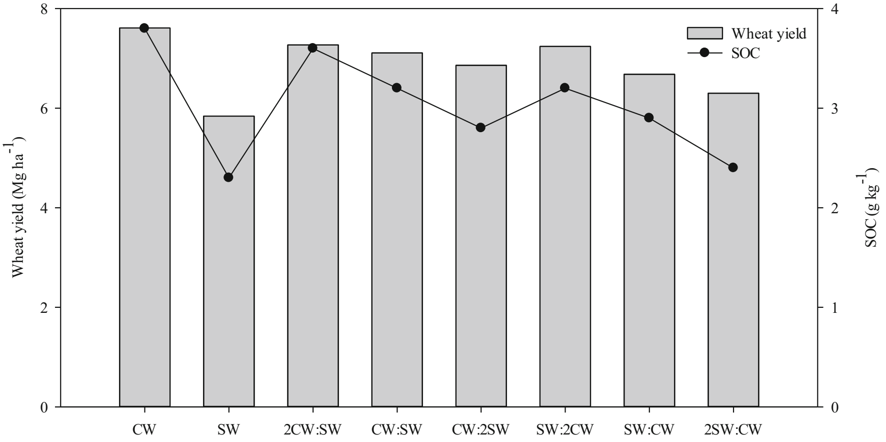


Fig. 15.4 Effect of irrigation treatments on wheat yield and SOC

(C) Management of Sodic Water

(i) Conjunctive Use.

Co-application of canal (CW) and sodic waters (SW) not only manages sodicity hazards but also increases crop production and improves soil health (Choudhary et al. 2019) (Fig. 15.4). This is predominantly pertinent where CW availability is either uncertain or insufficient, and farmers frequently pumping sodic ground water for additional irrigation. Different alternatives include (a) mixing variable quality waters in the delivery network generating water accessibility for every crop under different soils (Minhas and Gupta 1992), (b) periodic use of irrigation water (good and bad) quality according to critical stages of the crop (Choudhary 2017).

Earlier studies (Bajwa and Josan 1989a,b,c; Choudhary et al. 2006; Chauhan et al. 2007; Minhas et al. 2007; Choudhary and Ghuman 2008) showed that irrigation on an alternate basis with good-quality CW and SW keep the ESP at low level and helps in improving different crop yields. Recently, Sekhon et al. (2019) also reported that under limited availability of good-quality irrigation water supply, cyclic use of saline-sodic ground water (GW) and good-quality CW irrigation (1: 1) is beneficial for getting greater marketable potato tuber yield in loamy sand soil. Besides, Choudhary (2017) reported higher (93–98%) of cotton and wheat crops with the initiation of irrigation with CW than SW and involved one SW (2CW: SW, CW:SW). On the other hand, after 6 years of cropping, the reduction in seed cotton yield was noticed to be comparatively more (18–23%) than in the wheat yield (10%) with cycles (SW:CW, 2SW:CW) involving one CW. Furthermore, during the next 6 yrs. (7–12 yrs), long-standing sustainability of different cycles (2CW, SW, CW:SW, and SW:2CW) was established when relative yields of wheat and cotton (90–96%) were optimal. Therefore, the results confirmed that for guaranteeing better germination when cotton was irrigated with good-quality CW before sowing.

D) **Irrigation Period.**

A common reference using sodic water is to relate small but regular irrigations used for reducing the results of poor hydraulic properties of sodic and sodic water irrigated soils.

(i) **Irrigation Method.**

Like saline conditions, allocation of water and salts in the sodic soil is primarily governed by different methods of irrigation. Irrigation methods cause disproportionate and non-uniformity in water application with low efficiency (50–60%) (Minhas 2012). On the other hand, more proficient irrigation ways like high-energy pressurized sprinklers and drip can be effectively used for regulating available water. Choudhary et al. (2010) showed that sodic water use in-furrow irrigation is more harmful on soil compare with drip irrigation in tomatoes.

(ii) **Leaching Requirement (LR).**

Reduction of salt concentration to acceptable limits can be achieved by leaching in salt-affected soils for good crop yield. The concept of LR holds good under circumstances with very low rainfall for achieving salt balance. However, it varies according to the rain, area, and climate. LR increases with a salt concentration in irrigation water and crop sensitivity to salt. For example, more salinity (30–50%) build-up was found in sandy soils when more saline water (50%) was applied to meet the LR. Even under RW and MW cropping systems, the application of 50% more water under sodic water irrigation was not useful to control salinity (Minhas and Bajwa 2001; Choudhary et al. 2011). To keep the low concentration of salt in the root area of the crop, a more suitable strategy appears to use the monsoon rainwater more efficiently for LR.

15.7 Conclusions

In this chapter, we have described the irrigation scheduling criteria and the main focal points to minimize the irrigation water losses while adopting the improved and pressurized irrigation methods for improving water productivity. Integration of conservation agriculture approaches with micro-irrigation methods may save precious water used for irrigation in agricultural crops and in increasing the water productivity under different cropping systems. Crop management approaches like tillage, crop establishment, residue management, and fertilizer management should be integrated with real-time water availability using modern methods and sensors to get higher water productivity and more water saving. In rainfed ecosystem, deficit irrigation approaches are the key to get higher water productivity and profitability.

Novel approaches like sub-surface drip irrigation (SSDI) should be promoted to catch the attention of farmers and to achieve the Govt. of India's mission *more crop per drop to contribute to Jal Shakti*. In NW India, water resources are depleting at a very faster rate, adoption of SMP in drip irrigation systems in conservation agriculture-based RW system are the need of the hour. There is an urgent need to study water balance components to investigate the soil water storage and water productivity under CA and CT farming. Quantifying the benefits of residue retention (in different densities, and types) and zero-tillage practices on the water balance, and the cropping system's ability to delimit water stress and improve yield. Policy reforms are needed to discourage the subsidy on methods and systems that cause low water productivity on a system basis. Reforms on safe water rights establishment to consumers, the decentralization and privatization of water management to a suitable stage, water pricing improvements, and the beginning of suitable water-saving tools for irrigation purposes should be in vogue. The haphazard use of poor-quality water could decrease crop yield and affect soil health. Therefore, the adoption of site-specific management alternatives could play a vital role in increasing crop productivity by checking salt build-up. There is a need for strong water management policies in real-world for increasing the use of saline-sodic water under field conditions.

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Optical Sensors for Rational Fertilizer Nitrogen Management in Field Crops

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Abstract

Fertilizer nitrogen (N) is one of the most important nutrient inputs in global crop production. The general fertilizer N management practices in field crops consist of applying preset N doses at specified growth stages in multiple splits. Blanket or soil-test-based recommendations ignore temporal and spatial variability in soil N supply and crop demand for N and thus could not help improve N use efficiency beyond a certain limit. Synchronizing plant N demand and fertilizer N supply is a proven fertilizer management approach to improve N use efficiency. In-season plant growth comprehends the total N supply to plants from different sources, thus in-season plant N status and plant biomass could be a better indicator of the N availability to crops than soil testing. Optical sensors have emerged as efficient diagnostic tools for estimating crop N status and yield of the crops and thus help

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guide site-specific need-based fertilizer N topdressings. Relationships between spectral properties measured using optical sensors and plant N concentration, total N uptake, various agronomic and yield parameters of major field crops have been extensively studied. This chapter reviews the results of investigations carried out for assessing plant N status and developing rational fertilizer nitrogen management strategies using different kinds of optical sensors in wheat, rice, maize, and cotton.

Keywords

Cotton · Maize · Optical sensors · Precision N management · Rice · Wheat

Abbreviations

CCCI	Canopy chlorophyll content index
CI	Chlorophyll index
CRI	Crown root initiation
DAS	Days after sowing
DDSR	Dry direct-seeded rice
GC	Ground cover
INSEY	In-season estimation of yield
IR	Infrared
IRVI	Inverse ratio vegetation index
LAI	Leaf area index
LCC	Leaf color chart
LNA	Leaf nitrogen accumulation
LNC	Leaf nitrogen concentration
MT	Maximum tillering
N	Nitrogen
NDVI	Normalized difference vegetation index
NIR	Near-infrared
NUE	Nitrogen use efficiency
RE	Red edge
RI	Response indices
RVI	Ratio/red vegetation index
SA-NDVI	Soil adjusted normalized difference vegetation index
SPAD	Chlorophyll meter
TCC	Total canopy chlorophyll
UAN	Urea ammonium nitrate
URN	Uniform rate of nitrogen
VI	Vegetation index
Vis	Visible
VRN	Variable rate of nitrogen

16.1 Introduction

Nitrogen (N) is an essential nutrient, widely applied to agricultural soils worldwide to support crop yields. Global inorganic N fertilizer use has increased about ten-fold over the past 50 years (from 11.7 Tg N yr.$^{-1}$in 1961 to 107.6 Tg N yr.$^{-1}$in 2017 (IFASTAT 2020). The need to meet the increasing food production demands of a burgeoning population will require further increases in fertilizer N use. However, both living beings and ecosystems are being negatively affected by the increasing escape of reactive N from croplands to the environment (Galloway et al. 1995; Yadav et al. 2020). It has been estimated that the escape of reactive N from soil-plant systems to the atmosphere may cause economic damage of more than double the value that N fertilizers add to farm income (Sutton et al. 2011; Meena et al. 2020). World resources institute speculated a 58% increase in greenhouse gas emissions from agricultural production by 2050 (WRI 2019).

Developing countries consumed more fertilizer N (60 Mt) than the developed countries (40 Mt) in 2018 (IFADATA 2020). Until 1989, the consumption of total fertilizer N in developed countries was higher than in developing countries, however afterward the consumption decreased in the developed world while developing countries are still continuing higher N use in crop lands (Fig. 16.1). Low population pressure and improved N use efficiency (NUE) with the adoption of precision N management practices resulted in reduced consumption of N fertilizer in developed countries. The government policies of providing subsidized N fertilizers in some developing countries restrain farmers to adopt need-based N use recommendations and are the major cause of excessive N use in these regions. Shifting these subsidies from fertilizer N to the price of produce can help improve N use efficiency and mitigate environmental footprints of excessive N use in developing countries.

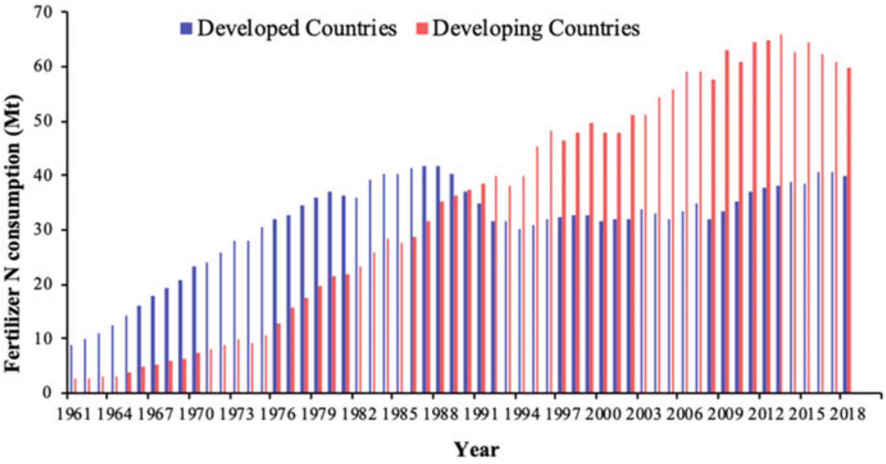

Fig. 16.1 Consumption of total fertilizer nitrogen (N) in developed and developing countries since the 1961s. *Data source*: IFADATA (2020)

The efficient fertilizer N use on smallholder farms can help avoid excessive application of fertilizer N without any reduction in crop yields but with reduced ecological turbulences such as global warming through nitrous oxide emissions, pollution of water bodies such as nitrate leaching and runoff, and environmental pollution through ammonia emissions. Providing precision N management decisions using soil chemical analysis had always been a challenge as available indices of soil N are not very reliable (Nayyar et al. 2006; Kumar et al. 2018; Kumar et al. 2020). The available soil N pools exist mainly in organic forms and thus researchers are using soil organic carbon (SOC) content as an index of soil N supply (Pathak et al. 2003). However, the kinetics of N mineralization from soil organic matter and dynamics of N supply to plant could not be easily understood from soil organic carbon analysis and thus questions the philosophy of using SOC content for making fertilizer N recommendations (Varinderpal-Singh et al. 2017).

Fixed fertilizer N applications based on the soil test-based N recommendations at fixed time ignore spatial and temporal changes in soil N supply and plant N demand and lead to poor fertilizer NUE (Varinderpal-Singh et al. 2010; Dobermann et al. 2003). The fertilizer management strategies such as deep placement, controlled-release N fertilizers, and nitrification inhibitors do improve fertilizer NUE but to a limited extent (Bijay-Singh and Singh 2017; Kumar et al. 2021). In recent years the precision N management research has shifted from the concept of '*feeding soil*' to '*feeding plant*' and it revolves around finding means and ways to synchronize plant N demand with fertilizer N supply using plants as indicators. The leaf color chart (LCC), chlorophyll meter (SPAD meter), and optical sensors (GreenSeeker and Crop Circle) have emerged as the potential precision gadgets for need-based N fertilizer management in rice (Bijay-Singh et al. 2002, 2012, 2015; Varinderpal-Singh et al. 2007; Ali et al. 2014, 2015), wheat (Raun et al. 2002; Bijay-Singh et al. 2017, 2018; Varinderpal-Singh et al. 2012, 2017) and maize (Varinderpal-Singh et al. 2011; Ali et al. 2018). The optical sensors can measure the N status of the canopy rather than individual leaves as in the case of SPAD meter and LCC.

The reflectance properties (such as hyperspectral reflectance and radiance measurements) of plant canopies in the visible, near-infrared (NIR), and infrared (IR) regions of the spectrum (350–2500 nm) consider both leaf chlorophyll content and crop biomass simultaneously rather than only the chlorophyll content as in SPAD meter and LCC based measurements. We have attempted to review the available information about optical sensors in terms of different kinds of optical sensors, algorithms used for major field crops—wheat, rice, maize, and cotton, and how fertilizer N management guided by optical sensors compare with blanket recommendations as well as other need-based N management techniques.

16.2 Optical Sensors for Precision N Management

Several optical sensors are available and these are mainly categorized as hyperspectral and multispectral sensors. The multispectral sensors viz. Crop Circle (450–880 nm) and CropScan (440–1750 nm) have a spectral resolution of 10–20 nm

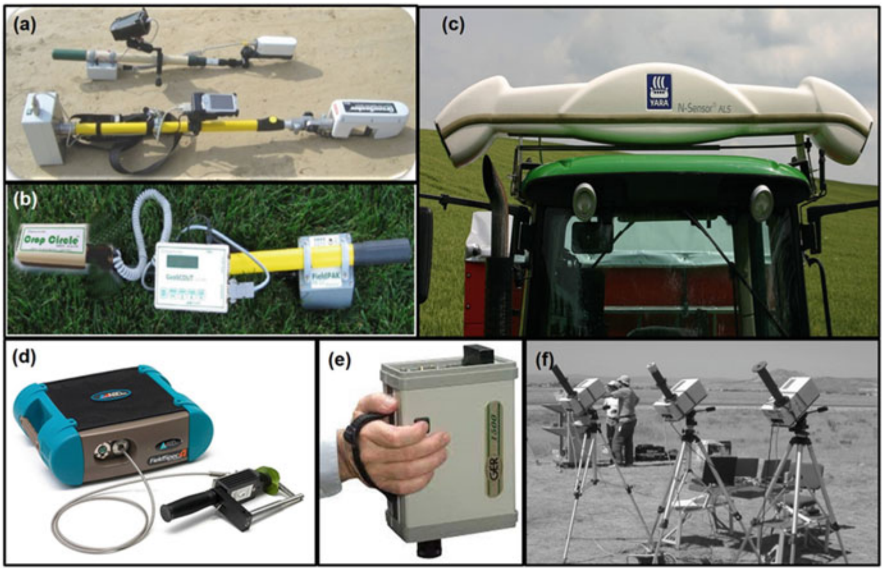

Fig. 16.2 Different types of optical sensors used in precision N management research (**a**) GreenSeeker (**b**) CropCircle (**c**) Yara N sensor (**d**) FieldSpec spectroradiometer (**e**) GER 1500 spectroradiometer, and (**f**) LI-COR 1800 spectroradiometer

with limited 3 to 16 wavebands and estimate the variations in leaf area index (LAI) and biomass (Darvishzadeh et al. 2006), and N content (Roberts et al. 2009). The hyperspectral sensors such as ASD FieldSpec measures reflectance in the wavelength range of 350–2500 nm. The hyperspectral sensors have a very fine spectral resolution of 1–2 nm with 2150 continuous wavebands and these are capable of providing detailed biophysical and biochemical information. The most used optical sensors (Fig. 16.2) in precision N management research are briefly described below:

16.2.1 Green Seeker Optical Sensor (N Tech Industries, Inc., USA)

GreenSeeker canopy reflectance sensor emits red (650 ± 10 nm) and NIR (770 ± 15 nm) wavebands with a field of view (FOV) ranging from 52 to 145 cm^2 facing downwards. The optimal height range for sensing with GreenSeeker is between 71–112 cm. The leaf chlorophyll content controls the reflectance of the visible light, while the structure of mesophyll tissues governs the reflectance of the NIR spectrum (Campbell 2002). The reflectance measured as spectral vegetation indices including inverse ratio vegetation index (IRVI), normalized difference vegetation index (NDVI), red vegetation index (RVI), and soil adjusted-NDVI (SA-NDVI) that provide a predictive assessment of photosynthetic efficiency, productivity, and yield (Peñuelas et al. 1994; Ma et al. 2001; Raun et al. 2001; Bronson et al. 2011), and are sensitive to leaf area index (LAI) and green biomass (Peñuelas et al. 1994). The sensor has been used for managing fertilizer N in a variety of crops including wheat (Raun et al. 2002; Heege et al. 2008; Bijay-Singh et al. 2011, 2013, 2017), rice (Tubanã et al. 2012; Xue et al. 2014; Bijay-Singh et al. 2015), barley (Soderstron et al. 2010), corn (Tremblay et al. 2009), cotton (Raper et al. 2013), and sugarcane (Singh et al. 2006; Portz et al. 2012).

16.2.2 Crop Circle (Holland Scientific Inc., Lincoln, NE)

Crop Circle ACS 210 is a hand-held sensor having two detectors that measure reflected modulated light from 400–680 nm and 800–1100 nm, and between the optimal sensing heights of 51 to 91 cm with an acquisition interval ranges from 1 to 20 samples per second. The sensor has a FOV of roughly 36° by 6° from the sensor. Bronson et al. (2011) calculated the crop canopy reflectance by Crop Circle ACS 210 using amber NDVI (aNDVI) in the visible light source at 590 nm (amber) as follows:

$\text{aNDVI} = (R_{\text{NIR}} - R_{\text{amber}})/\ (R_{\text{NIR}} + R_{\text{amber}}).$

where, R_{NIR} – reflectance in the NIR region, and R_{amber}– reflectance in the amber region. Shaver et al. (2010, 2011) and Raper et al. (2013) also used Crop Circle ACS 210 crop reflectance sensor for predicting N status in maize and cotton, respectively. Roberts et al. (2009) calculated the chlorophyll index (CI) values using the Crop Circle ACS 210 crop sensor and directs the in-season N application in maize.

Crop Circle ACS 470 is a multispectral crop canopy sensor that measures the reflectance from 440–800 nm using12.5 mm interference filters. The sensor has an oval FOV of roughly 36° by 6° range and covers about 0.09 m^2 area. This multispectral Crop Circle ACS 470 sensor was used by Cao et al. (2015, 2017) for precision N management and determining the aboveground biomass variability in winter wheat. Sharma et al. (2015) and Li et al. (2014) evaluated the different spectral indices calculated from the reflectance data generated by Crop Circle ACS 470 sensor for predicting yield and N uptake in maize to direct in-season N fertilization.

16.2.3 Yara N-Sensor (Yara International ASA, Oslo, Norway)

Yara N-sensor consists of two diode array spectrometers measuring light reflectance between 450–900 nm wavelengths with a bandwidth of ±5 nm. At each end of the sensor unit, two fiber optic inputs (12° field of view) are located for viewing both the left and right of the sensing platform and connected to one spectrometer. The sensor mounted on a cab or tractor captures the light reflectance by covering the crop area of approximately 50 m^2. The sensor estimates the crop N status and accordingly adjusts the N fertilizer rate being applied to the crop (Raper et al. 2013; Raper and Varco 2015). The sensor captures the crop variability in high resolution and performs data analysis within a short span of time (i.e., 10 readings per second).

16.2.4 CropScan Radiometer (CropScan, Inc. Rochester, MN)

It is multispectral radiometer with 16 pairs of filters (centered at 450, 470, 500, 530, 550, 570, 600, 630, 650, 670, 700, 780, 820, 870, 1600, and 1700 nm wavelength). The sensor is adjusted approximately 0.5 m above the plant canopy and reflectance data is measured between 2 h and 20 min before solar noon. The overcast sky and shadow must be avoided during reflectance data collection. For the calibration of the radiometer, an opal glass is used that provides the same irradiance alternatively to the upward and downward sensors at an angle of 45° to the sun. Yabaji et al. (2009) made the cotton canopy reflectance measurement using CropScan MSR 16 at 1.2 m above the canopy and calculated green vegetative index (GVI $= R_{820}/R_{550}$). Rambo et al. (2010) derived the NDVI values from CropScan MSR 16 radiometer by recording the reflectance at red (660 nm) and NIR (760 nm) wavelength for determining the plant N status in maize. Gianquinto et al. (2019) assessed the canopy reflectance in tomatoes using CropScan MSR 16 radiometer and derived reliable vegetation indices for precision N management.

16.2.5 Portable Spectroradiometers

Researchers used a variety of spectroradiometers developed by different manufacturers. The most commonly used spectroradiometers incudes FieldSpec FR (Analytical Spectral Devices Inc., USA), Daedalus AA440 (Ann Arbor, MI, USA), GER 1500 (Spectra Vista Corp., Poughkeepsie, New York), and LI-COR 1800 (LI-COR, Inc., Lincoln, NE). FieldSpec FR is a single-beam field spectroradiometer measuring over the 350 to 2500 nm wavelength range using photodiode array spectrometer and fast scanning spectrometers. The instrument scans very rapidly, acquiring single spectra in milliseconds through its fiber optic input that enhances the functionality of the instrument for a wide range of remote sensing studies. Several studies have reported that the use of FieldSpec FR spectroradiometer improves the accuracy of predicting leaf N concentration (LNC) and in-season fertilizer N management in cotton compared to time-consuming and costly determination of plant tissue N content under laboratory conditions (Tarpley et al. 2000; Read et al. 2002; Zhao et al. 2004, 2005a, 2005b, 2007).

Daedalus AA440 collects the reflectance in the range of 400–2400 nm waveband in 4–8 nm increments. The reflectance data is measured by dividing the observed radiance data with the radiance measurement from known reflectance under the same sunny conditions. The data measurement is made on plant rows when the individual plants are touching within a row. Infield, a frame is set up in the direction perpendicular to rows and fitted with a pair of meter sticks (one above the plant canopy and the other at ground level directly below the upper meter stick). Spectral measurements are taken by pointing the sensor head of the spectroradiometer downward at 1.5° so that an area of 2.5 cm diameter is covered for a given measurement. Maas (1997, 1998) determined the canopy density by measuring the reflectance of cotton leaf canopies using the Daedalus model AA440 portable spectroradiometer at 600–700 nm (red) and 800–900 nm (IR) wavebands.

GER 1500 measures ground-based radiometric data in the waveband of 268 to 1095 nm with 1.5 to 2.1 nm bandwidth. The instrument has an 18 deg FOV fiber optic at a nadir view angle approximately 1.8 m above the soil surface. Read et al. (2002) and Thorp et al. (2017) collected canopy reflectance data in the 350 to 1050 nm waveband using GER 1500 portable spectroradiometer to estimate the plant biomass and N content in cotton and durum wheat, respectively.

LI-COR 1800 measures the reflectance in the wavelength range from 400–1100 nm range at the waveband of 2–10 nm. Lee et al. (2008) assessed the N concentration in rice by measuring canopy reflectance at 735 nm using LI-COR 1800 spectroradiometer. Buscaglia and Varco (2002) correlated the leaf reflectance data with cotton leaf N content and reported better estimates of cotton N status at 550 nm using the LI-COR 1800 spectroradiometer.

16.2.6 Near-Infrared Analysis (NIR Systems, SliverSpring, MD)

The sensor is equipped with a scanning grating monochromator and a spinning sample-cup-module. Leaf discs of 2.54 mm diameter were cut by a punch from each leaf, placed in a sample cup, and analyzed by NIRA 6500 spectrometer over the spectral range of 1100–2500 nm at 2 nm intervals. Saranga et al. (1998) and Riley and Canaves (2002) used NIRA to estimate cotton LNC and decide N fertilization. Towett et al. (2013) applied NIRA to analyze the N content in cowpea leaves and further the crude protein content was estimated.

16.3 Spectral Indices

Numerous spectral indices employed by different workers using univariate and multivariate regressions from spectral reflectance data are summarized in Table 16.1.

16.4 Linking Optical Sensor Measurements, Plant N Concentration, Uptake and Crop Yield

16.4.1 Wheat (*Triticum aestivum* L.)

Raun et al. (2001) used reflectance measurements in the red and NIR regions to predict grain yield of winter wheat showing that grain yield and estimated yield were significantly correlated ($r^2 = 0.50$, $P > 0.0001$) at nine locations across 2 years. The estimated yield from six out of the nine locations explained 83% variability in measuring grain yield and thus helped refine the in-season N fertilizer application. Bijay-Singh et al. (2011) reported a correlation value ($r^2 = 0.61$; n = 75) between INSEY (in-season estimation of yield; NDVI divided by the number of growing

Table 16.1 Spectral indices and their formulations

Abbreviation	Indices	Type of reflectance[a]	Equation/formulation	References
aNDVI	Amber normalized difference vegetation index	Vis-NIR	$(R_{NIR} - R_{amber})/(R_{NIR} + R_{amber})$	Bronson et al. (2011)
CI-G	Chlorophyll index- green	Green-NIR	[b]Rn/Rg-1	Gitelson et al. (2003)
CI-MCARI	Combined index with modified chlorophyll absorption reflectance index	Vis-RE-NIR	MCARI / MTVI2	Eitel et al. (2007)
CI-RE	Chlorophyll index – Red edge	RE-NIR	Rn / Rre – 1	Gitelson et al. (2003)
CI-TCARI	Combined index with transformed chlorophyll absorption reflectance index	Red-RE-NIR	TCARI / OSAVI	Haboudane et al. (2004)
CVI	Chlorophyll vegetation index	Vis-NIR	$Rn \times Rr/Rg^2$	Vincini et al. (2008)
DGCI	Dark green color index	Vis	[(hue −60)/ 60 + (1 − saturation) + (1 − brightness)]/ 3.	Rorie et al. (2011); Karcher and Richardson (2003)
EVI	Enhanced vegetation index	Vis-NIR	2.5 (Rn-Rr) / (Rn + 6 × Rr-7.5 × Rb + 1)	Huete et al. (2002)
fWBI	Floating-position water band index	Red-NIR	$R_{900}/\min(R_{930}\text{-}R_{980})$	Peñuelas et al. (1997)
GLI	Green leaf index	Vis	(2 × Rg-Rr-Rb) / (2 × Rg + Rr + Rb)	Louhaichi et al. (2001)
GNDVI	Green normalized difference vegetation index	Green-NIR	(Rn-Rg)/(Rn + Rg)	Gitelson et al. (1996)
GOSAVI	Green optimized soil adjusted vegetation index	Green-NIR	(1 + 0.16) (Rn − Rg)/(Rn + Rg + 0.16)	Cao et al. (2013)
GRDVI	Green re-normalized difference vegetation index	Green-NIR	(Rn − Rg)/SQRT(Rn + Rg)	Cao et al. (2013)
GVI	Green vegetation index	Green-NIR	Rn/Rg	Bausch and Duke (1996); Bronson et al. (2003)
IRVI	Inverse ratio vegetation index	Red-NIR	Rr/Rn	Richardson and Wiegand (1977)

(continued)

Table 16.1 (continued)

Abbreviation	Indices	Type of reflectance[a]	Equation/formulation	References
MCARI	Modified chlorophyll absorption reflectance index	Red-RE	$[(R_{700} - R_{670}) - 0.2(R_{700} - R_{550})]\ (R_{700} / R_{670})$	Daughtry et al. (2000)
MGSAVI	Modified green soil adjusted vegetation index	Green-NIR	$0.5 * [2 * Rn + 1 - SQRT((2 * Rn + 1)\ 2–8 * (Rn - Rg))]$	Cao et al. (2013)
MTCI	MERIS total chlorophyll index	RE-NIR	$(R_{750} - R_{710}) / (R_{710} - R_{680})$	Dash and Curran (2004)
NDREI	Normalized difference red edge index	RE-NIR	$(Rn\text{-}Rre)/(Rn + Rre)$	Gitelson and Merzlyak (1994)
NDVI or RNDVI	Normalized or red normalized difference vegetation index	Red-NIR	$(Rn\text{-} Rr)/(Rn + Rr)$	Rouse et al. (1974); Tucker (1979)
NDVI (modified) Or mND	Modified normalized difference index	Vis-NIR	$(R_{750} - R_{705}) / (R_{750} + R_{705} - 2R_{445})$	Sims and Gamon (2002)
NDVI canopy	Normalized difference vegetation index canopy	Red-NIR	$(Rn - Rr)$ canopy / $(Rn + Rr)$ canopy	Muharam et al. (2015)
NGRDI	Normalized green-red difference index	Vis	$(Rg\text{-}Rr)/(Rg + Rr)$	Tucker (1979)
NIR or RNIR	Near-infrared index (also called infrared band reflectance)	NIR	R_{810}/R_{560}	Gutierrez et al. (2012)
OSAVI	Optimized soil adjusted vegetation index	Red-NIR	$(1 + 0.16)\ (Rn\text{-} Rr)/(Rn + Rr + 0.16)$	Rondeaux et al. (1996)
PCA	Principal component analysis index	Green-blue-red	$0.994 \lvert R_r\text{-}R_b \rvert + 0.961 \lvert R_g\text{-}R_b \rvert + 0.914 \lvert R_g\text{-}R_r \rvert$	Saberioon and Gholizadeh (2016)
PSRI	Plant senescing reflectance index	Vis-NIR	$(R_{680}\text{-}R_{500})/R_{750}$	Merzylak et al. (1999)
RDVI	Re-normalized difference vegetation index	Vis-NIR	$(R_{800} - R_{670})/(R_{800} + R_{670})^{0.5}$	Rougean and Breon (1995)

RVI or SRI	Ratio vegetation index (also called simple ratio or red vegetative index)	Red-NIR	Rn/Rr	Jordan (1969); Pearson and Miller (1972); Bronson et al. (2003); Barati et al. (2011)
RVI (modified)	Modified ratio vegetation index	Red-RE-NIR	$(R_{750}\text{-}R_{900}) / (R_{690}\text{-}R_{710})$	Gutierrez et al. (2012)
SRI (modified)	Modified simple ratio index	Vis-NIR	$(R_{750} - R_{445}) / (R_{705} - R_{445})$	Sims and Gamon (2002)
SAVI/SA-NDVI	Soil adjusted vegetation index	Red-NIR	(1 + 0.5) (Rn- Rr)/(Rn + Rr + 0.5)	Huete (1988)
SAVI (modified)	Modified soil adjusted vegetation index	Red-NIR	$0.5\{2 \text{ x Rn} + 1 - \sqrt{}[2 \text{ x Rn} + 1]^2 - 8(\text{Rn-Rr})]\}$	Qi et al. (1994)
SIPI	Structure insensitive (or independent) pigment index	Blue-red-NIR	$(R_{800}\text{-}R_{445}) / (R_{800}\text{-}R_{680})$	Peñuelas et al. (1995)
TCARI	Transformed chlorophyll absorption reflectance index	Red-RE	$3[(R_{710} - R_{680}) - 0.2(R_{700} - R_{550})] (R_{700}/R_{670})$	Haboudane et al. (2002)
TCC_{leaf}	Total canopy chlorophyll leaf	Green-red	$[1/(R550,_{Leaf} + R700,_{Leaf})] \times GC^c$	Muharam et al. (2015)
TCC_{canopy}	Total canopy chlorophyll canopy	Green-red	$[1/(R600,_{Canopy} + R700,_{canopy})] \times GC$	Muharam et al. (2015)
TCC_{scene}	Total canopy chlorophyll scene	Green-red	$NDVI_{canopy} \times GC$	Muharam et al. (2015)
TCI	Triangular chlorophyll index	Red-RE	$1.2 (R_{700}\text{-}R_{550}) - 1.5 (R_{670} - R_{550}) \times \sqrt{}(R_{700}/R_{670})$	Haboudane et al. (2008)
TGI	Triangular green index	Vis	$-0.5 [^d\lambda r - \lambda b) (Rr - Rg) - (\lambda r - \lambda g) (Rr - Rb)]$	Hunt Jr. et al. (2011)
TVI	Triangular vegetation index	Vis-NIR	0.5 [120 (Rn-Rg) – 200 (Rr-Rg)]	Broge and Leblanc (2001)
TVI (modified) or MTVI2	Second modified triangular vegetation index	Vis-NIR	$1.5[2.5(\text{Rn-Rg})\text{-}2.5(\text{Rr-Rg})]/\sqrt{}[(2 \times \text{Rn} + 1)^2 - 6 \times \text{Rn-}5 \times \sqrt{}(\text{Rr})\text{-}0.5]$	Haboudane et al. (2004)
VARI	Visible atmospherically resistant index	Vis	(Rg-Rr) / (Rg + Rr-Rb)	Gitelson et al. (2002)

(continued)

Table 16.1 (continued)

Abbreviation	Indices	Type of reflectance[a]	Equation/formulation	References
WBI	Water band index	NIR	R_{900}/ R_{970}	Peñuelas et al. (1997)
WDRVI	Wide dynamic range vegetation index	Red-NIR	(a × Rn-Rr) / (a × Rn + Rr) “a” is the weighting coefficient with a value varying from 0.1 to 0.2.	Gitelson (2004)

[a] NIR – Near-infrared; Vis – Visible; RE – Red edge

[b] Rb, Rg, Rr, Rre, Rn are the reflectances for blue (450–520 nm), green (520–600 nm), red (630–700 nm), red edge (700–750 nm), and near-infrared (750–900 nm) bands, respectively

[c] GC – Ground cover

[d] λb, λg, and λrrepresent blue, green and red wavebands, respectively

degree days from planting to sensing) and grain yield at the maximum tillering (MT) stage. Bijay-Singh et al. (2017) reported robust relationships between INSEY and actual wheat yields both at 2nd ($r^2 = 0.64$) and 3rd ($r^2 = 0.86$) irrigation stages of the wheat in northwestern India.

Hodgen et al. (2005) compared different in-season N response indices (RI) based on NDVI (RI_{NDVI}) and plant height ($RI_{PLANTHEIGHT}$) at Feekes stage 4–6 and found accurate N fertilizer management decisions with RI_{NDVI}. RI_{NDVI} was determined by dividing NDVI data of the plot supplied with sufficient N with the NDVI data of the test plot. Similarly, $RI_{PLANTHEIGHT}$ was measured in the same way as RI_{NDVI}, where the mean plant height of N-rich plots was divided by the mean plant height of test treatment. However, Arnall et al. (2009) found a positive relationship between NUE and RI at harvesting ($RI_{HARVEST}$) for different N rates ($r^2 = 0.37$) across multiple years and demonstrated that the relationship improved ($r^2 = 0.45$and $r^2 = 0.56$) when both RI_{NDVI} and $RI_{HARVEST}$ were included in the model. Girma et al. (2006) found GreenSeeker NDVI strongly associated ($r^2 = 0.78$) with final grain yield. Julien et al. (2011) also revealed the usefulness of measuring crop reflectance using GreenSeeker for INSEY.

Satellite images generated with high (QuickBird and WorldView-2 satellite data) and moderate (Landsat) spatial resolution can also be used to estimate variability in yield and crop growth (Kumhalova and Matejkova 2017). Wright et al. (2004) evaluated remote sensing as a tool to determine leaf N. Aerial imagery acquired three spectral bands centered on the green (0.55 μm), red (0.67 μm), and NIR (0.80 μm). Satellite-based spectral data was acquired by QuickBird II imagery whereas ground-based reflectance data was measured with GreenSeeker optical sensor and ASD Field Specspectroradiometer. Flag leaf N and reflectance ($r^2 = 0.52–0.80$) were significantly correlated. The sensor-based measurements successfully estimated N stress.

The satellite image data can well explain yield variability regardless of the spatial resolution of the images (Domínguez et al. 2015). Images acquired in early growth stages showed differences according to the sensor used that influence the NDVI values. Different vegetation indices were used for estimating winter wheat N status using Crop Circle green, red, and NIR wavebands and evaluated their potential improvements over GreenSeeker NDVI and ratio vegetation index (RVI). Cao et al. (2015) observed that the Crop Circle ACS-470 sensor (three-band user-configurable) improved the N estimation in winter wheat compared with the GreenSeeker sensor (two fixed band). The Crop Circle normalized difference red edge index/green optimized soil adjusted vegetation index (NDREI/GOSAVI) and CI – Red Edge (CI-RE) give better aboveground biomass assessment than GreenSeeker NDVI. Significantly high correlation was observed between N nutrition index and Crop Circle green re-normalized difference vegetation index (GRDVI) ($r^2 = 0.78$) and modified green soil adjusted vegetation index (MGSAVI) ($r^2 = 0.77$) compared to NDVI ($r^2 = 0.47$) and RVI ($r^2 = 0.44$). A study conducted by Cao et al. (2017) indicated that the Crop Circle significantly improve the estimation of grain yield ($r^2 = 0.62$) and plant N uptake ($r^2 = 0.78$) of wheat over that by GreenSeeker sensor ($r^2 = 0.33$ and 0.60, respectively).

Combined vegetation indices provide greater sensitivity to the assessment of leaf chlorophyll content (Daughtry et al. 2000). The combined index determined from the ratio of transformed chlorophyll absorption reflectance index to optimized soil adjusted vegetation index (TCARI/OSAVI) enhanced sensitivity to chlorophyll content ($r^2 = 0.81$) and reduced the background soil reflectance (Haboudane et al. 2002). Eitel et al. (2007) also observed improved prediction of flag leaf N and chlorophyll content in wheat ($r^2 > 0.70$) using a combined index ratio of modified chlorophyll absorption reflectance index to second modified triangular vegetation index (MCARI/MTVI2). Eitel et al. (2008) reported that calculated vegetation indices were very well correlated to LAI ($r^2_{\mathrm{LAI}} = 0.84$) but less to chlorophyll meter readings ($r^2_{\mathrm{chlorophyll}} = 0.46$) and flag leaf N ($r^2_{\mathrm{flag\ leaf\ N}} = 0.29$). The MCARI/MTVI2 index offered acceptable resistance to LAI ($r^2 = 0.01$) and sensitivity to chlorophyll ($r^2 = 0.70$) and flag leaf N ($r^2 = 0.54$). Thus, the combined index MCARI/MTVI2 may provide better in-season crop N prediction to enhance grain protein concentration and efficient N management in wheat.

16.4.2 Rice (*Oryza sativa* L.)

Limited studies are reported on assessing plant N concentration using optical sensors in rice. Ali et al. (2014) studied the correlation between grain yield and GreenSeeker NDVI measurements at different growth periods of dry direct-seeded rice (DDSR). This revealed that NDVI recorded at 42 days after sowing (DAS) had low r values which improved as growth progressed to 56 DAS ($r = 0.51$) and ($r = 0.80$) at 70 DAS before declining ($r = 0.75$ and 0.67 at 84 and 98 DAS, respectively). Less canopy coverage, interference of soil properties, and low N uptake lead to poor *r* values at early growth stages which improved with the canopy coverage at 70 DAS coinciding with panicle initiation. In northwestern India, Bijay-Singh et al. (2015) reported relationships with r^2 values 0.51, 0.45, and 0.49, respectively, between observed grain yield and grain yield, predicted with GreenSeeker at 42, 49, and 56 days after transplanting of rice.

Zhang et al. (2017) established the relationships between GreenSeeker NDVI values and LNC for N diagnosis during the rice growth period. Coefficients of correlation as high as 0.90 between leaf N accumulation (LNA) and NDVI with different cultivars, soil types, and N levels suggested that GreenSeeker can be reliably used to predict in-season rice N status. Xue et al. (2004) studied canopy spectral reflectance and plant N concentration for nondestructive monitoring and plant N diagnosis in rice under different N fertilization, irrigation, and plant population levels. LeafNconcentrationwas well correlated to the ratio index of NIR/green (R_{810}/R_{560}), with the best correlation ($r^2 = 0.87$) at the jointing stage while poorly correlated to green reflectance band (560 nm). A linear relationship ($r^2 = 0.91$) between total LNA and the ratio of NIR to green (R_{810}/R_{560}) was observed, independent of N level and growth stages, and was found useful for in-season plant N diagnosis in rice. Chang et al. (2005) measured canopy reflectance spectra over the entire rice growth period and developed two multiple regression models

(NIR/red and NIR/green) to estimate rice yields. The regression models derived from canopy reflectance data measured at the booting stage can successfully predict rice grain yield. Liu et al. (2017) assessed the quantitative relationships between NDVI and growth indices (LAI, aboveground dry matter, and grain yield) in two rice varieties – Japonica and Indica. The correlation of NDVI with LAI and dry matter decreases with growth stages and showed maximum at the jointing stage ($r^2 = 0.80$ and 0.79, respectively). NDVI exhibited a significantly positive correlation with grain yield at all stages and most reliably predicted the grain yield at the booting stage.

Cao et al. (2013) evaluated 43 vegetation indices derived from three wavebands (green, red edge, and NIR) of Crop Circle ACS-470 for estimating rice N status. The vegetation index (MCARI) exhibited consistent high correlations with biomass ($r^2 = 0.79$) and plant N uptake ($r^2 = 0.83$) of rice across growth stages, varieties, and site-years. A study conducted at Jiansanjiang, Northeast China compared the rice canopy reflectance data from GreenSeeker and Crop Circle optical sensors (Cao et al. 2016). The results indicated that both the GreenSeeker ($r^2 = 0.66$) and Crop Circle ($r^2 = 0.71$) worked well at the stem elongation stage for predicting the rice grain yield potential.

16.4.3 Maize (***Zea mays*** **L.)**

Active sensor-based technology can be efficiently used to assess plant N and aboveground biomass after the V6 crop growth stage in maize (Mistele and Schmidhalter 2008; Shaver et al. 2010). Liu and Wiatrak (2011) observed that NDVI recorded at V8 and R1 stages are a good indicator to assess corn grain yield. Rambo et al. (2010) also reported the potential of using canopy reflectance measured with the CropScan and GreenSeeker optical sensors as an indicator of corn N level. Li et al. (2014) estimated the N status of maize using different vegetation indices with a Crop Circle canopy sensor and WorldView-2 satellite broad bands. The canopy chlorophyll content index (CCCI) at the V6-V7 ($r^2 = 0.65–0.68$) and V10–V12 ($r^2 = 0.76–0.80$) was well correlated with maize plant N concentration and uptake. The other red edge-based indices (MTCI, NDREI, and CI-RE) also performed well across bandwidths for predicting plant N uptake ($r^2 = 0.76–0.91$) than NDVI and RVI ($r^2 = 0.54–0.80$) at the V6–V12 stages. CCCI uses three bands (red, red-edge, and NIR) in comparison to NDVI and NDREI, and was considered the best index for estimating plant N uptake at the V6 and V7 ($r^2 = 0.65–0.68$), V10–V12 ($r^2 = 0.80–0.82$) stages (Li et al. 2014).

The Crop Circle NDREI based INSEY values ($r^2 = 0.17–0.20$) were found to be significantly correlated with grain yield as compared to GreenSeeker NDREI based INSEY ($r^2 = 0.06–0.08$) at the V6 stage (Sharma et al. 2015). At V12 stage, Crop Circle NDVI ($r^2 = 0.18$), Crop Circle NDREI ($r^2 = 0.18$), GreenSeeker NDVI ($r^2 = 0.20$) based INSEY values were related to yield while GreenSeeker NDREI ($r^2 = 0.04–0.06$) based INSEY values were not. GreenSeeker emits and measures light reflectance in four bands – red (660 nm), two red-edge (710 and 735 nm), and

NIR (774 nm) while Crop Circle emits and measures light reflectance in three bands – red (670 nm), red-edge (730 nm), and NIR (760 nm). It was concluded that at the V6 stage NDVI and NDREI were similar in relation to yield, while at the V12 stage the NDREI performed better than NDVI and proved useful in developing late-season N application algorithms in maize (Sharma et al. 2015). Shaver et al. (2010) observed that at the V8 stage of maize, coefficients of correlation between GreenSeeker NDVI and Crop Circle aNDVI with N rate were lower as compared to NDVI values at the V10 and V12 stage. In contrast, Shaver et al. (2011) reported high r^2 values with applied N rate between NDVI readings from both GreenSeeker and Crop Circle and grain yield at V12 and V14 growth stages for determination of N variability in maize.

Raun et al. (2008) applied N fertilizer before planting in automated gradients to assess the midseason N rates using optical sensor-based yield prediction models. This approach assumes that midseason biomass estimation using NDVI sensor readings is directly related to maize yield and helps guide fertilizer N topdressings at later stages. Ali et al. (2018) found that NDVI measured at 50 DAS gave the highest r-value (0.76) with grain yield and was the appropriate stage to apply a corrective fertilizer N dose in maize. Bragagnolo et al. (2013) used the Yara N optical sensor to assess the N status of maize and analyzed coefficients of correlation between vegetation index (VI; based on the reflectance at 730 and 760 nm wavelength) and plant properties. VI was positively correlated with the N uptake ($r^2 = 0.87$) and negatively with the plant N content ($r^2 = 0.53$). The relationship between maize VI and N uptake was found to be strongly influenced by the crop phenological stage (Mutanga and Skidmore 2004). It was observed that up to V10 and V12 stages (later stages) of maize (Heege et al. 2008; Portz et al. 2012), a saturation of VI readings decreases crop sensor efficiency.

Using airborne VNIR micro hyperspectral imager (Micro-Hyperspec® VNIR model, Headwall Photonics, Fitchburg, MA, USA) and multispectral sensor (MCA-6, Tetracam, Inc., California, USA) drone high correlation ($r^2 = 0.89$) was observed between TCARI/OSAVI indices and LNC. But LNC exhibited weak relations ($r^2 < 0.2$) to remote sensing indices (NDVI, RDVI, or OSAVI), which were not able to accurately predict the crop N nutritional status (Gabriel et al. 2017).

16.4.4 Cotton (*Gossypium hirsutum* L.)

Leaf reflectance measured using LI-COR 1800 spectroradiometer (LI-COR, Inc., Lincoln, NE) in the 400 to 850 nm range revealed that N deficiency increased leaf reflectance across the whole measured spectrum and provided a better indicator of crop N status at early growth stages (Buscaglia and Varco 2002). Reflectance measurements at 550 nm were shown to be a sensitive means of estimating N status in cotton at squaring (bud stage) and flowering (blooming stage) stages. Feibo et al. (1998) and Wood et al. (1992) found positive correlations between leaf chlorophyll levels and LNC ($r^2 = 0.66–0.80$, $n = 120$), but changes in chlorophyll concentration with growth stages were much smaller than changes in LNC. Leaf hyperspectral reflectance showed a similar pattern and there was a rapid increase in leaf reflectance at 556 and 710 nm with the decreasing fertilizer N rate but variation was small between growth stages. Carter and Spiering (2002) and Zhao et al. (2003) found that leaf reflectance measured at 580 and 700 nm wavelengths were the most closely associated with leaf chlorophyll and the most sensitive to fertilizer N application rate. A study of the relationship between cotton leaf chlorophyll and hyperspectral reflectance revealed the best correlation at the spectral band of 807.6 nm (Boggs et al. 2003). Cotton leaf chlorophyll was significantly related to cotton yield, and thus acts as an indicator of N deficiency. Therefore, the authors suggested that hyperspectral reflectance can be potentially used as a tool for scheduling N topdressings in cotton. Measuring total canopy chlorophyll (TCC) using GER 1500 portable field spectroradiometer (Spectra Vista Corp., Poughkeepsie, NY, USA) at the individual leaf (TCC_{Leaf}), canopy (TCC_{Canopy}), and scene (TCC_{Scene}) levels revealed that $TCC_{Leaf}$was a better index to estimate leaf N ($r^2 = 0.89$) followed by TCC_{Canopy} ($r^2 = 0.76$) and TCC_{Scene} ($r^2 = 0.50$) (Muharam et al. 2015).

The slope of the relationship between LNCand seed cotton yield at different growth stages after emergence has been shown to gradually decrease as plants approach maturity and cotton is highly sensitive to N deficiency at the early flowering stages (Saranga et al. 1998). Sui and Thomasson (2006) revealed the importance of integrating plant reflectance [measured at four spectral wavebands of blue (400 to 500 nm), green (520–570 nm), red (610–710 nm), and NIR (750–1100 nm)] with plant height to improve correlation and better prediction of LNC. Zhao et al. (2005a) screened wavelengths from 400–2500 nm to determine an appropriate reflectance as an index of LNC and leaf chlorophyll content. This revealed that reflectance at 517 and 701 nm was well correlated to LNC, whereas reflectance at 551 nm and 708 nm had the best correlation with leaf chlorophyll content (Zhao et al. 2005a). Tarpley et al. (2000) and Read et al. (2002) suggested using reflectance ratios (ratio of reflectance at the red edge to near infrared) instead of single reflectance for improved prediction of cotton LNC.

Zhao et al. (2004) found that single spectral index or canopy variable (LAI, leaf chlorophyll content, dry biomass, and canopy chlorophyll density) provided less than 45, 48.8, 61.6% accuracy in predicting crop N status, respectively, at early, mid and late-season growth stages of cotton, whereas using multi-vegetation indices improved the accuracy to 74.4, 83.1 and 89.4%, respectively for the same growth stages (Zhao et al. 2004). The evaluation of red-NIR vegetation indices in discriminating cotton canopies by N stress revealed that a single vegetation index was able to correctly classify only 30–45% of samples by N rate (Zhao et al. 2005b). Investigations of the relationships between canopy spectral reflectance, biomass, and cotton lint yield revealed that canopy reflectance response to N treatments depends on both growth stage and wavelength. Canopy reflectance at 550 nm (red) and 710 nm (NIR) turned out to be high in low N treatment during cotton's squaring and fruiting stage. Relative lint yield showed the strongest correlation (r^2 of 0.56–0.89; $P < 0.01$) with reflectance indices at the early flower stage (70–75 DAS). Thus, measuring the canopy reflectance indices at the early flowering stage of cotton could better predict cotton yield (Zhao et al. 2007).

Multispectral plant-soil reflectance measurements in the wavelength range 447–1752 nm revealed the peak of red reflectance at early growth stages while with growth the NIR reflectance increased (Li et al. 2001). The relationship between NDVI and N uptake followed a sigmoidal pattern indicating that NDVI increased quickly during vegetative stages and reaches a maximum before the highest N uptake level. Raper et al. (2013) observed that fertilizer N rates significantly affected the NDVI measured with a Crop Circle, GreenSeeker, and Yara N-sensor at all the growth stages. The multispectral vegetative indices based on leaf N and cotton biomass estimated at early squaring, early bloom, and peak bloom stages revealed that GVI and green normalized difference vegetation index (GNDVI) correlated better with leaf N than red or ratio vegetation index (RVI) and red normalized vegetation index RNDVI (Bronson et al. 2003). Cotton biomass and lint yield correlated more often with RVI/RNDVI than GVI/GNDVI. These findings suggested that GVI and GNDVI values are effective in predicting the leaf N compared to RVI and RNDVI, which are effective in assessing cotton biomass (Bronson et al. 2003).

The comparison of four spectral reflectance indices NDVI ($[R_{900} - R_{680}]/[R_{900} + R_{680}]$), SRI (simple ratio index, R_{780}/R_{670}), NIR (R_{810}/R_{560}), and RVI modified ($[R_{750} - R_{900}]/[R_{690} - R_{710}]$, for predicting cotton yield revealed that NDVI explained 47% of the variation in lint yield whereas SR, NIR and RVI indices explained 56, 60, and 58% variations, respectively. This indicates that using SR, NIR, and RVI at peak bloom can increase the accuracy in the prediction of lint yield (Gutierrez et al. 2012). The NDVI correlations with leaf N and plant height generally increased from pre-squaring to peak flowering (Raper et al. 2013). Across sensors (Crop Circle, GreenSeeker, and Yara N sensor) the sensitivities to plant height, leaf N, and total N content, the Yara N-Sensor exhibited the strongest relationship with plant height, leaf N, and total N content followed by GreenSeeker and Crop Circle ACS-210 (Raper et al. 2013). Although all the sensors were sensitive to variations in plant height, however, they failed to consistently predict cotton leaf N status and did not correlate strongly with fertilizer N rate. Thus, there is a need to develop some correction factors by coupling one sensor with another for the development of the N fertilizer algorithm.

Plant height and NDVI are two different indicators of plant growth. Plant height is mainly associated with fertilization, row spacing, and plant density (Maddonni et al. 2001) while NDVI is related to the leaf's area, angle, color, thickness, and moisture (Hatfield et al. 2008). Zhou and Yin (2014) found that LNC has a stronger correlation with fertilizer N application rates than plant height and NDVI. Motomiya et al. (2009) showed that NDVI values (measured by GreenSeeker) increased with the level of fertilizer N application while red/NIR values exhibited the inverse trend. The positive linear relationship of NDVI with leaf N, CI, and LAI demonstrate the effectiveness of an optical sensor in determining the N deficiency in cotton. Studying the correlation between LNC and reflectance at 16 wavebands (450–1700 nm), Bronson et al. (2005) observed that leaf N had a weak negative correlation with green reflectance. The study of reflectance of cotton canopies across four wavelengths 550 nm (green), 650 nm (red), 720 (red-edge), and 840 nm (NIR) about leaf N, total plant N, and lint yield revealed that leaf N, total plant N content and lint yield were strongly correlated with reflectance at red-edge region compared to reflectance at the green and red region. The red-edge indices were more appropriate indicators of crop N demand (Raper and Varco 2015).

16.5 Using Optical Sensors for Making Precision N Management Decisions

The yield response to fertilizer N depends on inherent soil fertility and agro-climatic conditions. Excessive N fertilization beyond the optimum level did not improve yield. Rather yields may decrease due to increased insect-pest incidence. In developing countries, the standard recommendations formulated by agricultural scientists are generally based on the anticipated crop response to fertilizer N and are related to the organic carbon status of the soil. But it ignores the spatial and temporal variability in soil N supply during crop growth. The site-specific N management provides an alternative approach to soil test recommendations that ensure synchronizing the soil N supply from different sources and crop N demand. Assessment of spectral characteristics of radiations reflected from the canopy can assess leaf chlorophyll content and crop N status. A concept of “response index” (RI) was developed by Raun et al. (2002) to consider spatial and temporal variability in soil N supply through INSEY while drawing site-specific fertilizer N recommendations in wheat. Now several algorithms for different crops and locations are available for predicting in-season crop yield and N uptake (Bijay-Singh and Ali 2020). The outcome of the research on using optical sensors for precision N management decisions in different field crops is reviewed in the following sub-sections.

16.5.1 Wheat (*Triticum aestivum* L.)

The farmers in northwestern India and Pakistan generally apply a third dose of fertilizer N to spring wheat at the MT stage after applying two split doses at planting and at CRI stages. However, the appropriate criteria to decide the optical sensor-based N application in wheat were lacking. Bijay-Singh et al. (2013) found that spectral properties measured at MT stage can be best used to decide need-based fertilizer N application in wheat after applying fixed N doses at planting and CRI stage. The results of three-year experimentation in four wheat cultivars using GreenSeeker revealed that if INSEY values were found to be 0.005 or 0.011 then need-based topdressing at MT stage can lead to an increase in grain yield by 1.0 or 0.5 t ha^{-1}, respectively.

Raun et al. (2002) found improvement in NUE by more than 15% when fertilizer N was applied on the basis of INSEY, and RI compared with blanket N use practices. Unlike GreenSeeker that records spectral information in red and near-infrared wavebands, the Yara N-Sensor/FieldScan can record spectral information from twenty wavebands including red and NIR, and thus, more vegetation indices can be computed that relate better to N status than NDVI. Tremblay et al. (2009) compared the Yara N-Sensor/FieldScan and the GreenSeeker for managing N applications in spring wheat. It was observed that each sensor had its own sensitivity characteristics and algorithms developed for variable-rate N (VRN) applications using one sensor cannot be transferred directly to another sensor. Bijay-Singh et al. (2011) observed that GreenSeeker guided fertilizer N applications to wheat in northwestern India resulted in high yield levels and high NUE. It was found that the application of 90 kg N ha^{-1} in two equal splits at planting and CRI stage was the appropriate prescriptive fertilizer N dose. Further refinements made in the optical sensor-based fertilizer N management strategy for irrigated wheat by Bijay-Singh et al. (2017) revealed that fertilizer N management based on GreenSeeker reflectance data resulted in high yield and NUE. Application of 30 and 45 kg N ha^{-1} at planting and CRI, respectively were found to be the appropriate N management before applying the GreenSeeker guided dose at Feekes 5–6 growth stage. GreenSeeker based fertilizer N use produced grain yield equivalent to those recorded from trials with blanket recommendation (120 kg N ha^{-1}), but had greater recovery (by 6.7–16.2%) and agronomic (by 4.7–9.4 kg grain kg^{-1} N applied) efficiency of applied N fertilizer. This showed that applying fixed dosage at planting and CRI met plant N demand until MT and that subsequent application of sensor-guided N dose at MT (coinciding with the second irrigation stage) sustained yield with higher fertilizer NUE in irrigated wheat. Ali (2020) found that the application of fertilizer N using the algorithm developed by GreenSeeker optical sensor yields similar to blanket fertilizer N recommendations (250 kg ha^{-1}) but with an average of 66 kg ha^{-1} less use of fertilizer N and improved agronomic (7.7 kg grain kg^{-1} N) and recovery (21.9%) efficiencies.

Non-destructive diagnosis of plant N status for drawing in-season fertilizer N application decisions with active canopy sensors such as GreenSeeker (Yao et al. 2014), CropCircle (Cao et al. 2013), and Yara (Tremblay et al. 2009) can overcome the limitations (time and cost for large field experimentations) of soil mineral N test-based plant N management strategies. Li et al. (2010) recommended the use of ratio vegetation index (RVI; a ratio of reflectance at NIR/Red) over NDVI (measured using GreenSeeker) to determine plant N uptake and found that NDVI became saturated when N uptake reached about 131 kg N ha^{-1} while RVI did not show saturation. Li et al. (2009) reported a saving of 305 kg N ha^{-1} and an increase in 48% N recovery efficiency using GreenSeeker based N management strategy compared to farmer's practice without affecting the yield of wheat averaged across site-years. Stone et al. (1996) reported that sensor-based variable N application of 61 and 55 kg N ha^{-1} (at Miller-2 and Perkins locations) respectively, saved 31 and 57 kg N ha^{-1} compared to fixed N rate application (92 and 112 kg N ha^{-1}) which resulted in savings of \$14.08 and \$24.51 fertilizer per hectare without affecting the grain yield.

Variable-rate N topdressings using the available algorithms did not always result in high grain yield or N savings (Samborski et al. 2016). The researchers observed inconsistent advantages in terms of grain yield, grain protein content, and NUE and advised the development of robust algorithms using multi-year, multi-location data, a derivative of topographical and soil conditions involving information of rainfall patterns and soil moisture. The variable N rate recommendations were found beneficial in fields initially fertilized with relatively low N rates that entail a more appropriate allocation of the same amount of total N using optical sensors. Diacono et al. (2013) reviewed that precision technologies can be used for collecting information about spatial and temporal differences within the field to match inputs to site-specific field conditions. It has been concluded that both the measurement and understanding of soil spatial variability and wheat N status are necessary before making N decisions. Airborne images and proximal sensing have the potential for predicting crop N status based on in-season management approaches. The use of different hyperspectral vegetation indices for real-time sensing and fertilization accounted for higher yield, NUE, and savings of fertilizer N.

16.5.2 Rice (*Oryza sativa* L.)

Rationalizing fertilizer N use in rice using optical sensors is not extensively studied. Bijay-Singh et al. (2015) developed GreenSeeker based site-specific fertilizer N use strategies based on red and NIR spectral response from rice canopies in northwestern India. They developed an algorithm for rice on the lines of Raun et al. (2002) and applied sensor-guided fertilizer N doses at the panicle initiation (PI) stage of the crop. A prescriptive N dose of 30 and 45 kg N ha^{-1} at transplanting and active tillering, respectively, was found to be sufficient before making GreenSeeker guided need-based N application decision at PI stage. This led to equivalent grain yields compared to standard practice, but with less N use and thus better recovery (by 5.5–21.7%) and agronomic efficiency of applied N fertilizer.

The PI stage was also shown to be the most appropriate stage for predicting grain yield and applying site-specific GreenSeeker guided fertilizer N dosing in DDSR (Ali et al. 2015). Similar rice yield levels were obtained by applying a prescriptive N dose of 60 kg ha^{-1} in two or 90 kg ha^{-1} in two or three equal splits, followed by a corrective GreenSeeker guided N dose in comparison with a general recommendation, but with less N use, improving NUE by over 12% (Ali et al. 2015). Yao et al. (2012) used the GreenSeeker sensor to collect canopy reflectance data for making appropriate fertilizer N topdressing at stem elongation or booting stage and achieved 48% higher partial factor productivity of fertilizer N without compromising grain yield. Yao et al. (2014) also studied rice N status using NDVI and RVI indices obtained with a GreenSeeker sensor showing that when plant N uptake reached about 100 kg N ha^{-1}, the NDVI became saturated while RVI did not. The relationship between GreenSeeker readings and plant N uptake was stronger at the stem elongation stage than at heading.

16.5.3 Maize (*Zea mays* L.)

Ali et al. (2018) studied N management using a GreenSeeker sensor in maize for developing and validating an algorithm for improving N application. The V9 growth stage of maize was found appropriate for applying a corrective N dose. Application of 150 kg N ha^{-1} in two equal split doses, followed by a corrective optical sensor-guided N dose produced grain yield equivalent to the general recommendation of 300 kg N ha^{-1} with less N use. Shavers et al. (2014) used both the CropCircle amber sensor and GreenSeeker red sensor and found that these performed equally well for recommending fertilizer N dose at V12 growth stage of maize. However, the authors suggested that more efforts are required to increase its efficiency by optimizing an algorithm accounting for bare soil reflectance and insensitivity of red reflectance at saturation leaf area indices.

Bragagnolo et al. (2016) found VRN 140 kg ha^{-1}, prescribed by Yara N sensor, increased NUE and grain yield production compared to a uniform rate of N (URN; 0, 70, 140, and 210 kg ha^{-1}). The URN and VRN management produced similar grain yields but the major benefit of the VRN was reducing fertilizer N consumption and environmental pollution. Predicting N response using optical sensors at early growth stages is difficult (Bushong et al. 2018). It was found that reliable differences in reflectance index values could be detected only beyond V7/V8 growth stages so that optical sensor-based N management strategies could be used only when the crop has reached the advanced stages.

Swamy et al. (2015) evaluated GreenSeeker guided fertilizer N management in sweet corn (*Zea mays saccharata* L.). Blanket recommendation of applying 150 kg N ha^{-1} in two and three splits was compared with the fertilizer N dose topdressings at NDVI less than 0.6 or 0.8 based. It was inferred that split application of 150 kg N ha^{-1}followed by NDVI 0.8 based N topdressings can efficiently manage fertilizer N in sweet corn. Bragagnolo et al. (2013) evaluated the efficiency of Yara N optical sensor-based N fertilization on the corn vegetation indices at different sites. The VRN using a sensor was evaluated with traditional single-rate N fertilization (TSF). The increase in corn N uptake was observed as a major benefit of VRN in relation to TSF in the zones where the plant N nutrition status is poor. It was observed that climatic conditions affect the corn N uptake under VRN. High and unevenly distributed rainfall causes leaching of mineral N while well-distributed rainfall concentrates the N in soil and meets the crop N demand. The sensor-based VRN provided more accurate fertilizer N application decisions for efficient N use. Scharf et al. (2010) reported results of reflectance ratios-based N fertilization in 53 maize fields and observed yield benefit of 110 kg grain ha^{-1} with the savings of 16 kg N ha^{-1}over the fertilizer rates applied as per farmer's practice.

16.5.4 Cotton (*Gossypium hirsutum* L.)

Bronson et al. (2011) measured cotton canopy reflectance using GreenSeeker and Crop Circle optical sensors to inform fertilizer N topdressings at the first square and early mid-bloom stages. Soil test-based N recommendation was evaluated in comparison with two optical sensors-based N management strategies. In the first strategy (S1), fertilizer N was given at 50% of the soil test N dose. When NDVI in the S1 plot fell significantly below the NDVI of plots with 100% soil test N, fertilizer application was increased. The second optical sensor-based N management strategy (S2), included an initial N application equal to 100% soil test N and was increased to match the 150% soil test N dose based on NDVI. The S1 strategy averaged over 3 years lead to the application of 22 to 31 kg N ha^{-1} less than soil test-based N application and produced equivalent lint and seed yield. The fertilizer N application with S2 was 11 kg N ha^{-1} higher than the soil test N application but did not lead to any improvement in yield. Yabaji et al. (2009) studied fertilizer NUE, residual soil $NO_{3,}$ and lint yield as affected by fertilizer N rate in subsurface drip irrigated cotton; and by using canopy reflectance (measured by CropScan MSR16) based N management. Reflectance-based N management resulted in a saving of 17–28 kg N ha^{-1} compared with soil test-based N application, and produced equivalent lint yield.

Optimization of N supply to irrigated cotton was studied using NIRA as an indicator for N fertilization in irrigated cotton (Saranga et al. 1998). Field experiments were conducted with three nitrogen treatments: (1) basal dose of 150 kg N ha^{-1}; (2) NIRA-guided fertilizer N application; and (3) control treatment with no-N. In the NIRA treatment, N was applied only when the leaf N concentration dropped to a level of the control treatment when determined weekly. At 56 days after emergence (DAE), before any application of N fertilizer all the treatments showed similar LNC of 34 g kg^{-1} dry matter (DM). In treatment where 150 kg N ha^{-1} of the basal dose was applied, LNC was found to be 42 g kg^{-1} DM. In the NIRA-guided treatment, when LNC dropped below the level of the no-N treatment, application of 60 kg N ha^{-1}(30 + 30 kg N ha^{-1}) increased the leaf N content by 5–6 g N kg^{-1} DM within 3 days. The NIRA-guided N application produced lint yield equivalent to soil test-based N application with a huge saving of fertilizer N, whereas the lint yield of no-N treatment was significantly low.

Mullen et al. (2003) proposed the use of a RI ($NDVI_{high\ N\ plot}/NDVI_{zero\text{-}N\ plot}$) to guide reflectance-based in-season N fertilizer application. Raun et al. (2005) estimated the field RI using a "calibration stamp" approach consisting of a 9 × 9 m^2 grid with nine, 1-m^2 areas where UAN (urea ammonium nitrate) was applied at the rate of 0–112 kg ha^{-1}. The N calibration stamp assisted farmers to decide the appropriate N dose but the small size of calibration stamps made it difficult to characterize the N response in large fields. Therefore, Raun et al. (2008) developed a "ramp calibration strip" approach which consisted of 2-m or wider strips of 16 fertilizer N rates (e.g., 0–220 kg N ha^{-1}). Bronson et al. (2012) established field fertilizer N calibration ramps for cotton in Lubbock County, Texas in 2008 and 2009. Sixteen steps of N calibration ramps were prepared and fertilizer N rates were varied from 22.4 to 179 kg ha^{-1} in 11.2 kg N ha^{-1} steps. Canopy reflectance was measured at mid and peak bloom stages using CropCircle (590 nm amber wavelength) and GreenSeeker (660 nm red wavelength) sensors. In-season NDVI response to N fertilizer was useful for rationalizing N used to produce optimum lint yield in cotton. Foote et al. (2016) also documented the usefulness of

GreenSeeker NDVI in assessing plant N status and predicting crop N requirement in cotton.

16.6 Future Research Needs and Limitations

The development of remote sensors to use spectral properties as an index of crop N content, biomass, and yield potential and thus efficiently manage in-season N topdressings constitutes a significant contribution to efficient fertilizer N management. The successful shift from blanket N recommendations to need-based fertilizer N management strategies demands organized campaigns to support farmers to understand the philosophy of achieving congruence in plant N demand and fertilizer N supply. Much work has been done to understand the relationships of various vegetation indices with plant N content, N uptake, agronomic, and yield parameters; however limited input is given on using crop sensor-generated data for efficient N use at on-farm locations. The algorithms developed for this purpose are not yet validated on geographical areas covering a wide range of agro-climatic conditions. Further, the algorithms are generally variety specific and a single algorithm may not work for all the varieties of a crop species. Crop geometry and agronomic practices also influence the validity of algorithms under different management conditions. A major limitation in using optical sensors for precision N management is that these can advise fertilizer N dose only once at the most responsive growth stage and cannot facilitate real-time N topdressing decisions at different growth stages during the cropping season. Defining prescriptive N dose and identifying the appropriate growth stage for employing optical sensors remains a prerequisite to use sensor-based N management.

Further, the available optical sensors are expensive and beyond the reach of the smallholder and marginal farmers in developing countries. Although, newly developed hand-held versions of GreenSeeker and Crop Circle are relatively cheap, but are still out of reach to the majority of the developing world and cannot compete with the economical and farmers-friendly gadget like PAU-Leaf Color Chart that provides a potential solution to achieve high NUE and grain yield with 50–75 kg ha^{-1} less fertilizer N (Swarbreck et al. 2019). Future research needs and limitations in the transfer of optical sensor-based fertilizer N management strategies to on-farm locations in developing countries are summarized as:

(a) Development of low-cost prototype crop sensors.
(b) Robust relationships to predict the yield of different crops grown in diverse agro-climatic regions and calculate in-season crop N requirements are not yet validated for broadacre adoption.
(c) Systematic research is required to understand how the amount of solar radiation being received in a region may influence spectral properties.
(d) The prerequisite prescription of basal N dose prior to need-based in-season N topdressings using optical sensors needs to be worked out on a scientific basis while considering the physicochemical and biological properties of the soils.

Inherent N supplying capacities in no-N plots needs to be studied at locations while working with crop sensor-based N management.

(e) The supply of nutrients other than N, e.g., irrigation, crop management practices, soil salinity, insect-pest incidence, weed infestation, and other stresses may affect optical reflectance and thus influence need-based N topdressing decisions. More work is required to adjust recommendations in view of these stresses.

(f) Appropriately managed over-fertilized reference Nstrip/plot of the same variety sown on the same date as of the field crop is the basic necessity to derive fertilizer N recommendations using optical sensors. It provides a benefit of considering spatial and temporal variability but is an additional job for the farmers. Establishing variety and growth stage-specific threshold NDVIs for homogenous agro-ecological zones may provide a substitute strategy of using optical sensors, but the reliability over the years and regions would remain uncertain as it would ignore considering spatial and temporal variability.

(g) Need-based fertilizer N management produces crops that are less susceptible to lodging, insects, and diseases. Further studies are required to establish the additional advantages of crop sensor-based N management practices.

(h) The crop sensor-based fertilizer N management ensures synchrony in N demand and supply, its impact on quality and weed ecology also needs to be evaluated.

16.7 Conclusions

Optical sensors have emerged as potential tools for improving the synchrony between plant nitrogen (N) demand and fertilizer N supply. The spectral properties measured using a variety of crop sensors have shown a strong relationship with plant N concentration, total N uptake, and various agronomic and yield parameters. The multiple kinds of vegetation indices provide the advantage of considering leaf greenness as well as biomass while calculating in-season plant N demand. Predicting crop yield and calculating the supplemental N dose required to achieve the expected yield is an appropriate strategy for making useful in-season fertilizer N topdressing decisions using crop sensors. Therefore, optical sensors can be used as reliable tools for efficient fertilizer N management in field crops, provided prerequisite initial N doses are worked out and robust algorithms are developed and validated to access temporal and spatial variability in soil N supply. However, there remains a challenge if expensive optical sensors can help achieve nitrogen use efficiency higher than the economical precision N management tools like leaf color chart.

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Remote and Proximal Sensing for Optimising Input Use Efficiency for Sustainable Agriculture

17

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Abstract

The proximal and remote sensing technology has steadily established its enormous potential in agriculture. This technology offers a cluster of benefits in input use efficiency, crop and soil productivity, food quality, and environment protection. An increase in crop production per unit of inputs (like water, fertilizers, seed, and pesticides, etc.) is required for sustainable agriculture. Multispectral and hyperspectral data and images are being used for monitoring crop phenology, spatial variability of soil nutrients, and detection of abiotic and biotic stresses in crops leading to the development of digital agriculture. Remote and proximal sensing can identify abiotic and biotic stresses at an early stage, which would give an opportunity for early management practices. Spatial maps of soil nutrients are used to prepare the prescription maps for variable rate application of inputs (like fertilizers, pesticides, and insecticides, etc.) coupled with a global positioning system to increase the input use efficiency for crop production. The hyperspectral data is useful for precision agriculture and soil fertility assessment, but more automated approaches to handle such big data are required. The lack of availability of cloud-free acquisitions with high spatial and temporal resolution satellite data has not been achieved the wider adoption of geospatial technology for monitoring agricultural systems across the globe. In order to enhance the use of satellite data for agricultural monitoring, the synchronized and harmonizing efforts are required to develop the human and institutional capacity in the world.

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Keywords

Agriculture · Proximal sensing · Remote sensing · Soil

17.1 Introduction

The global population is expected to reach 9 billion at the end of 2050, and global food production needs to be increased by 70% to feed this large population (Islam and Karim 2019). Due to the less scope of expansion of arable land globally, a significant portion of the increased demand for food production will be met by crop intensification which includes an increase in crop production per unit of inputs (like water, fertilizers, seed, and pesticides water, etc.). Despite success in increasing grain production with limited agricultural land, high-input farming has produced severe environmental problems. The excessive use of fertilizers for crop production causes economic imbalance besides environmental degradation due to water and nutrient losses (Yousaf et al. 2017). Therefore, a sustainable crop production system can be achieved through analysis of modern techniques having big data. This may help in increasing crop production through site-specific application of inputs with reduced environmental losses.

In the present scenario, precision agriculture is a key component of a sustainable agricultural system (Holland and Schepers 2013). Precision agriculture uses advanced information and data analysis techniques at various stages of crop input application (fertilizers, irrigation water, pesticides, etc.). It helps to improve crop production with reduced water and nutrient losses, thereby increasing the input use efficiency. Emerging technologies, such as remote sensing, Global Positioning System (GPS), and Geographic Information Systems (GIS) are promising tools for sustainable agriculture and increasing the input use efficiency (Bouma 1997; Kumar et al. 2018). The use of earth observation imagery provides spatial variability such as land use, soil, cropping pattern, water availability, etc. which can help to extrapolate the results of field studies at the local to regional level through spatial analysis. Also, the use of biophysical simulation models helps in conserving natural resources (soil and water) by analyzing the threats/ problems.

Precision Agriculture (or site-specific nutrient management) is based on the integration of information and production-based agriculture to increase productivity and profitability of the system employing site-specific farm management, which avoids production loss due to inadequate input application and harmful effects of excess chemicals and fertilizers (Auernhammer 2001; Kumar et al. 2021). The complex set of data is required for site-specific management which generally includes crop growth information, spatial variability in soil properties, daily micro-climate data (like canopy temperature, humidity, wind speed, direction, etc.), and nutrient status of the crop, etc. A combination of technologies like GIS, variable rate technology, GPS, modeling, and remote sensing (airborne and satellite-based) makes a way in precision farming and increasing input use efficiency (Waheed et al. 2006). Given the scope, it is not possible to present a comprehensive review of all the studies carried out about the application of remote sensing and GIS in enhancing the input use efficiency for sustainable agriculture in different parts of the world. The main objective of this chapter is to explain the use of remote sensing and GIS for identifying crop phenology, spatial variability of nutrients, variable application of inputs (fertilizers and pesticides), and detection of abiotic and biotic stresses in crops using remote sensing, proximal sensing, and GIS. An overview of the application of remote and proximal sensing in crop and soil management is given in Fig. 17.1.

17.1.1 Remote Sensing, Sensors, and Resolution

As per the conventional definition of remote sensing, it is the art and science that helps us to study any feature of our interest without being in contact with the same. The best example in order to understand remote sensing is our eyes. The human eye can sense electromagnetic radiation in the visible spectrum, and it need not be in contact with the feature of interest to see it or sense it. For earth observation purposes, sensors are usually mounted on a spaceborne or airborne platform and they work in visible to microwave region of electromagnetic spectrum. The sensor and the spaceborne platform carrying the sensor combined are commonly referred to as satellites. These are deployed into space for various earth observation applications. For example, the 24-satellite constellation launched by the United States Department of Defence in 1973 known as the Global Positioning System (GPS) is used for navigation purposes. The Moderate Resolution Imaging Spectroradiometer (or MODIS) is the sensor onboard Terra and Aqua satellites launched by National Aeronautics and Space Administration (NASA) in 1999 and 2002 respectively for observing the vegetation change, global snow cover change, coastal analysis, etc.

Any material in the universe, which has a temperature above 0 ^{O}K emits electromagnetic radiation. The sensors onboard a satellite senses the emitted energy from any feature or target of our interest. The range of the electromagnetic spectrum (in wavelengths) is listed below:

- X-rays and Gamma rays: shorter than 3 nm.
- Ultraviolet rays: 3 to 400 nm.
- Visible light: 400 nm to 700 nm.
  - Violet: 400–430 nm.
  - Indigo: 430–450 nm.
  - Blue: 450–500 nm.
  - Green: 500–570 nm.
  - Yellow: 570–590 nm.
  - Orange: 590–610 nm.
  - Red: 610–700 nm.
- Infrared: 0.7 to 300 μm.

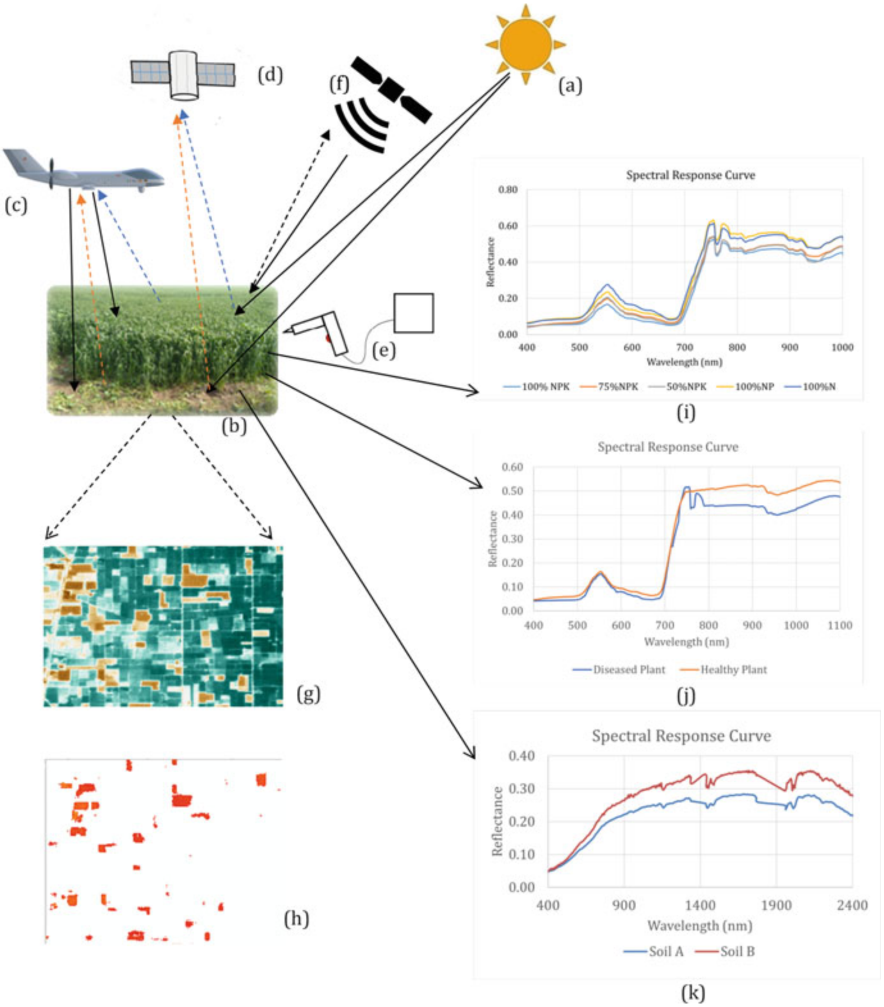

Fig. 17.1 Remote and proximal sensing for crop and soil management (**a**) sun/source, (**b**) target (crop and soil), (**c**) airborne sensors, (**d**) passive remote sensing, (**e**) proximal sensors, (**f**) active remote sensing, (**g**) crop and soil condition map (derived from sensor data), (**h**) prescription map generated using crop condition map for site-specific management, (**i**) spectral curve of abiotic stress in plants, (**j**) spectral response curve of healthy and diseased plants, and (**k**) spectral curve of soils

- Near-Infrared (NIR): 0.7–1.5 μm.
- Short Wavelength Infrared (SWIR): 1.5–3 μm.
- Mid Wavelength Infrared (MIR): 3–8 μm.
- Long Wavelength Infrared (LWIR): 8–15 μm.
- Far Infrared (FIR): longer than 15 μm.

- Microwaves: 1 mm to 1 m.
    - Ka band: 0.75–1.1 cm.
    - K band: 1.1–1.7 cm.
    - Ku band: 1.7–2.4 cm.
    - X band: 2.4–3.8 cm.
    - C band: 3.8–7.5 cm.
    - S band: 7.5–15 cm.
    - L band: 15–30 cm.
    - P band: 30–100 cm.
- Radio waves: 10 cm to 10 km.

The electromagnetic energy recorded by the sensor depends on the application. For example, for simple observation of vegetation health, the sensor needs to record energy in visible and NIR regions of the spectrum, but the sensor needs to record the thermal infrared region of the spectrum for monitoring agricultural stubble burning. When it comes to observing the surface deformation changes, the sensor needs to record energy in the microwave region (L or C- band). The decision to utilize which of the electromagnetic region depends purely on the application at hand.

The satellites sensors are classified into active sensors and passive sensors according to the source of illumination. The sensor using the sun's radiation as the source of illumination to record energy is referred to as passive sensor and the sensor having its own source of illumination to record energy is referred to as active sensor. Multispectral and thermal sensors are examples of passive sensors and the synthetic aperture radar or SAR sensors are an example of active sensors. A satellite put into orbit consisting of a sensor recording energy in the electromagnetic spectrum has to deal with one measurement—"resolution". Resolution is the ability to discriminate between targets. Resolutions are categorized as follows:

(a) *Spatial resolution*: Spatial resolution of an image indicates the ability to distinguish between two closely spaced objects. If the spatial resolution is high, the objects can be distinguished clearly and vice versa. The spatial resolution gives the size of the pixel of an image. The satellite altitude and instantaneous field of view (IFOV) define the spatial resolution.

(b) *Spectral resolution*: The ability of the sensor to sense the range of wavelengths is defined as its spectral resolution. The spectral resolution is higher or lower with respect to the narrowness of the wavelength range they can sense. The multispectral sensors detect 3–10 wavelength ranges, but the hyperspectral sensors detect 100 s to 1000s of narrow wavelength ranges.

(c) *Temporal resolution*: It is the time taken by the satellite to revisit the same area by completing one orbit. The revisit time depends on the satellite altitude and the satellite swath width. Satellites at higher altitudes can revisit in less than 24 hours but at lower altitudes, it may take 1 to 16 days, depending on the swath width of the satellite. A wide swath width satellite can revisit the same area at a 1-day interval like MODIS, but a narrow swath width satellite like the Landsat takes 16 days to revisit the same area.

(d) *Radiometric resolution*: Radiometric resolution of the sensor is its ability to differentiate between the smallest changes in the energy that it senses. Higher radiometric resolution indicates that the sensor can detect the smallest level of change in energy; for example, Landsat-8 has radiometry of 12-bit, meaning that the sensor can detect up to 4096 (2^{12}) levels of energy changes, whereas Landsat 1–7 sensors were 8-bit meaning they could sense up to 256 (2^8) levels of energy change.

As of now, there is not any sensor that can acquire images in high spatial, spectral, radiometric, and temporal resolution but a trade-off is required. It depends on the need at hand, for example, higher temporal resolution is required for weather observations, whereas higher spectral or spatial resolution is required for vegetation change observation.

17.2 Use of Remote and Proximal Sensing in Crop and Soil Management

Proximal and remote sensing techniques are considered a novel means for predicting soil properties, crop growth monitoring, and nutrient management. Proximal sensing refers to the use of ground-based sensors to measure the spectral reflectance when the detector of the sensor is in close range (~1 m or less) to the object of interest. Proximal sensing is accurate along with high spectral resolution, but it is time-consuming, labor intensive, and not suitable for large areas. The best example of proximal sensing is "spectroradiometer," a non-imaging field radiometer capable of providing both the intensity and spectral distribution of energy radiating from within the sensor's field of view.

Recent development in remote sensing technology makes it a key component in precision agriculture. Developing capabilities in data acquisition and data processing of ground, air, and satellite-based remote sensing made it possible to integrate remote sensing with precision agriculture. Besides this, proximal sensing is now used for increasing the input use efficiency for crop growth. In general, freely available spaceborne sensors (like Landsat and Sentinel) are economical along with frequent revisit time and suitable for large areas, but low spectral resolution and sensitivity to weather conditions affect real time monitoring of crop growth.

Variable spectral response in certain wavelength of different plant spices, biotic and abiotic stressed crops provides the database for site-specific management. A large volume of data can be generated using multispectral, hyperspectral, and microwave remote sensing in a cost-effective manner at very high spatial and temporal resolutions. This data can be used to retrieve the crop biophysical parameters, phenology, soil parameters, disease and pest incidence, moisture stress, nutrient stress, fertilizer, pesticide, and water management (Waheed et al. 2006). The major applications of remote and proximal sensing for enhancing the input use efficiency for crop production are:

(a) *Crop phenology*: The determination of crop phenological stages is required in many of the yield prediction and decision-making models used in precision agriculture. The manual recording of phenological stages in field is not a cost-effective method in a larger spatial extent, but the synoptic view and availability of historical data of remote sensing help in the determination of phenological events effectively (Zhang et al. 2001; Gitelson et al. 2004; Tang et al. 2016).

(b) *Soil nutrient mapping and variable rate application of fertilizers*: Mapping of soil fertility status and other soil parameters at field scale is required for site-specific nutrient management. These fertility status maps are used to prepare the prescription maps for variable rate application (VRA) of fertilizer coupled with GPS (Grisso et al. 2011).

(c) *Soil moisture estimation*: The estimation of soil moisture availability over a season is essential for the selection of crop and type of cultivar. Microwave remote sensing is commonly used to estimate soil moisture. Several active and passive microwave sensors have the ability to retrieve moisture-related information from soil (Nichols 2011).

(d) *Detection of abiotic and biotic stresses in crops*: Abiotic stresses lead to physiological and anatomical changes in plants resulting in yield reduction. Early detection of these stresses and changes can be detected using remote sensing which can help to manage abiotic stresses for minimizing the effect on crop yields (Stress and Jackson 1986; Beauchêne et al. 2019). The use of multi/hyperspectral data at a high spatial resolution can target the highly infested area for effective damage control and the reduce use of insecticide/pesticide in unaffected areas. This may help in improving the input use efficiency (Lowe et al. 2017).

17.3 Remote Sensing Based Methods of Phenology Detection

The information about periodic development of plants and their correlation with plant morphology (crop phenology) is one of the key components for enhancing input use efficiency. Phenological behavior varies with crop type and cultivars (Mendes et al. 2017). The phenological phases are mainly controlled by soil moisture, temperature, and human activity (Zhang et al. 2001; Kumar et al. 2021). The accurate monitoring of crop growth stages (or phenological stages) is one of the most important farm management factors that affect input use efficiency (Gitelson et al. 2004). In general, the following four transition points of plant phenology are driven by seasonal climatic change (Zhang et al. 2001):

1. Greenup (date of onset of vegetation),
2. Maturity (maturity as a result of end of growth),
3. Senescence (date of onset of senescence),
4. Dormancy (date of onset of full dormancy).

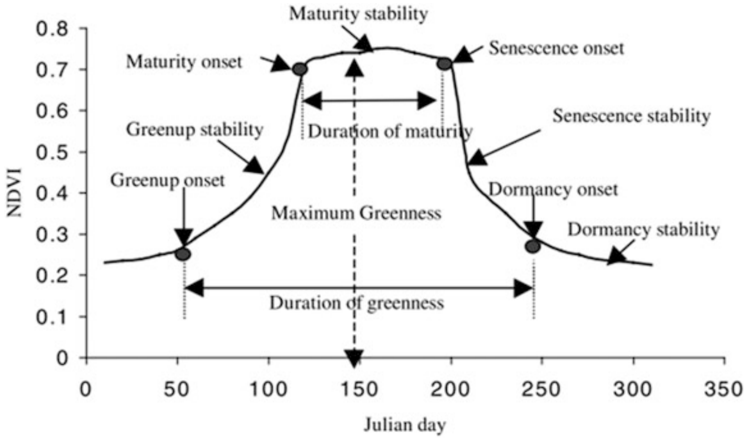

Fig. 17.2 Phenological transition points and phases (Source: Zhang et al. 2001)

Since the rate of growth and development will be different in each phase, nutrient and water requirements of the plant will be different. Therefore, identification of each phenologic transition point helps in nutrient and irrigation water management. Using the phenology curve given in Fig. 17.2 parameters about the vegetation growing season, the start of the season, end of the season, and length of the growing season can be extracted.

The unfavorable conditions during the Greenup stage will limit the size of leaves and thus biomass, at the beginning of maturity leads to impaired pollination and reduce the number of fertilized seeds, and at the terminal stage of maturity may lead to the formation of puffy seeds (Gitelson et al. 2004). The techniques for measuring plant phenology include recording phenological events by visual observations in field, periodic field photography, and remote sensing-based methods (Morisette et al. 2009). The visual and photographic methods involve an appreciable amount of cost and time. Therefore these methods are not useful for measuring phenological events at larger spatial and temporal scales. Remote sensing derived time-series datasets play a major role in detection of crop stages at large spatial scale (Jin and Eklundh 2014). There are a number of methods to study crop phenology that use high temporal resolution satellite data.

Most remote sensing methods for phenological measurements involve two important steps: preparation of time-series datasets of satellite derives vegetation indices and formulating a set of rules to determine phenological events using time series dataset (You et al. 2013). The first step involves the construction of smoothed time series dataset of satellite-derived vegetation indices. The smoothening of time series data is generally achieved by reducing the noise using filters and functions. The commonly used filters and functions are (a) Savitzky-Golay filter which uses the simplified least square procedures for smoothening the time series data (van Dijk et al. 1987), (b)asymmetric Gaussian function (Hird and McDermid 2009),

(c) Fourier filter (Beck et al. 2006; Atkinson et al. 2012) which reconstructs the smoothed time series by decomposing data into sine and cosine parts and filtering noise fluctuations, (d) double logistic function (Beck et al. 2006), (e) Whittaker smoother (Atkinson et al. 2012) which balances reliability and roughness of the data by fitting discrete series to discrete data, and (f) Changing-weight filter method (Zhu et al. 2012)

The local maximum/minimum in temporal vegetation profile is detected followed by filtering time sires with a three-point changing-weight filter. In the second step of phenological measurements, particular phenologic events are detected by analyzing the smoothed time series curves constructed in the first step and certain fixed rules (Sakamoto et al. 2010). The analysis of constructed smoothed curve includes the following methods:

(a) Maximum slope: The phenology events are identified based on the maximum or minimum slope of the vegetation index curve (Yu et al. 2003). When there is a rapid increment in vegetation growth, this indicates the start of the season, but a decrease in vegetation growth indicates the end of the season.
(b) Inflection point: This method has the advantage of easy implementation and discrimination of multiple growing seasons for land cover such as crops. Growing season discrimination is based on detecting points of maximum curvature in time series curve (Dash et al. 2010).
(c) Threshold method: In this method, phenology transition dates are defined based on the use of either a pre-defined or relative reference value (Fisher and Mustard 2007).
(d) Curvature change rate method:- Transition points of phenology are defined based on local minimum and maximum in curvature change rate of time series curves developed by the logistic models (Zhang et al. 2001).
(e) Moving average methods: The start of the season (end of the season) is defined as the day of the year when the time series curve crosses the moving average time series in an upward (downward) phase (Fisher and Mustard 2007).

You et al. (2013) used the NDVI data from NOAA-AVHRR with 15 days temporal resolution and 8 km spatial resolution to study the changes in crop phenology over a period of 2000–2003. They used the In-situ observation data of the start and end of the season of major crops from 261 agro-meteorological stations during 2000–2003. NDVI time series were generated for cropland pixels which were smoothed with Savitzky-Golay filter followed by a linear interpolation daily NDVI. The remote sensing derived thresholds from 2003 were verified with the observed start of season/ end of the season for 2000–2002. The average RMSE was 17.14 days for the start of the season and 17.44 days for the end of the season. Sakamoto et al. (2010) used the Two-Step Filtering (TSF) approach to detect the phenological stages in maize and soybean. They used time-series of Wide Dynamic Range Vegetation Index (WDRVI) derived from 8-day composite of MODIS with 250 m spatial resolution over 6 years (2003–2008). WDRVI time series were smoothed with a wavelet-based filter and then phenology scaling parameters were derived using shape-model fitting procedures. Their results showed that TSF can precisely estimate phenological stages for both soybean and maize. Galford et al. (2008) used a similar approach of time series generated with 8 days composite of Enhanced Vegetation Index (EVI) derived from MODIS data with 500 m spatial resolution for 5 year periods (2000–2005). (Hufkens et al. 2019) assessed the feasibility of near-surface remote sensing imageries (smartphone imageries) to monitor winter wheat crop phenology in north-western India. They used a series of pictures of individual farms acquired through inexpensive smartphones and quantified important phenological stages of winter wheat particularly the heading phase. Many of the techniques for crop phenology detection uses time series of various vegetation indices data with threshold-based and shape-based methods. However, the outcomes of these methods depend highly on temporal resolution of time series data used. In few cases, it is very difficult to obtain the time series data. To overcome these kinds of situations, (Yang et al. 2020) proposed a new method of identifying growth stages using single-date UAV imagery. They detected principal phenological stages of rice crop in the parts of southern China using convolutional neural network (CNN) incorporated with spatial pyramid pooling (SPP), transfer learning, and some external data. Their results were in agreement with ground-based measurements having an accuracy rate of 83.9% and mean absolute error (MAE) of 0.18.

17.4 Variable Rate Application of Crop Inputs Using Remote Sensing, GIS, and GPS

Optimum efficiency of inputs or profitability in crop production cannot be achieved with uniform application of inputs when the factors affecting crop growth and yield vary spatially within the field (Sawyer 1994). Variable Rate Application Technology (VRA) is a novel approach in improving the efficiency of inputs with the changed rate of application in response to spatial variability of the production factors which can be completely automated (Grisso et al. 2011). VRT not only answers the questions related to efficiency and profitability but also the environmental-related questions. Many researchers have acknowledged that VRA can bring economic, ecological benefits by improving the input use efficiency and thereby better sustainability in farming practices. A successful variable rate application system includes three components; (1) a sensing unit for detecting variations in weeds, disease intensity, soil gradients, and crop conditions within a field, (2) decision making a component that converts sensor readings to application intensity of inputs, and (3) an implement that carries out whole control method (Van Evert et al. 2012). Based on the use of Global Positioning System (GPS), two broad methods of VRA are map-based and sensor-based (Grisso et al. 2011).

A. Map based: In this method, a map called a prescription map is used which contains the information about application rates of inputs. These prescription maps are developed from soil maps generated using remote sensing and GIS technology, where spatial variability of the field is sensed by air or spaceborne sensors and the input rates are assigned to specific location. The prescription may appear as zones or

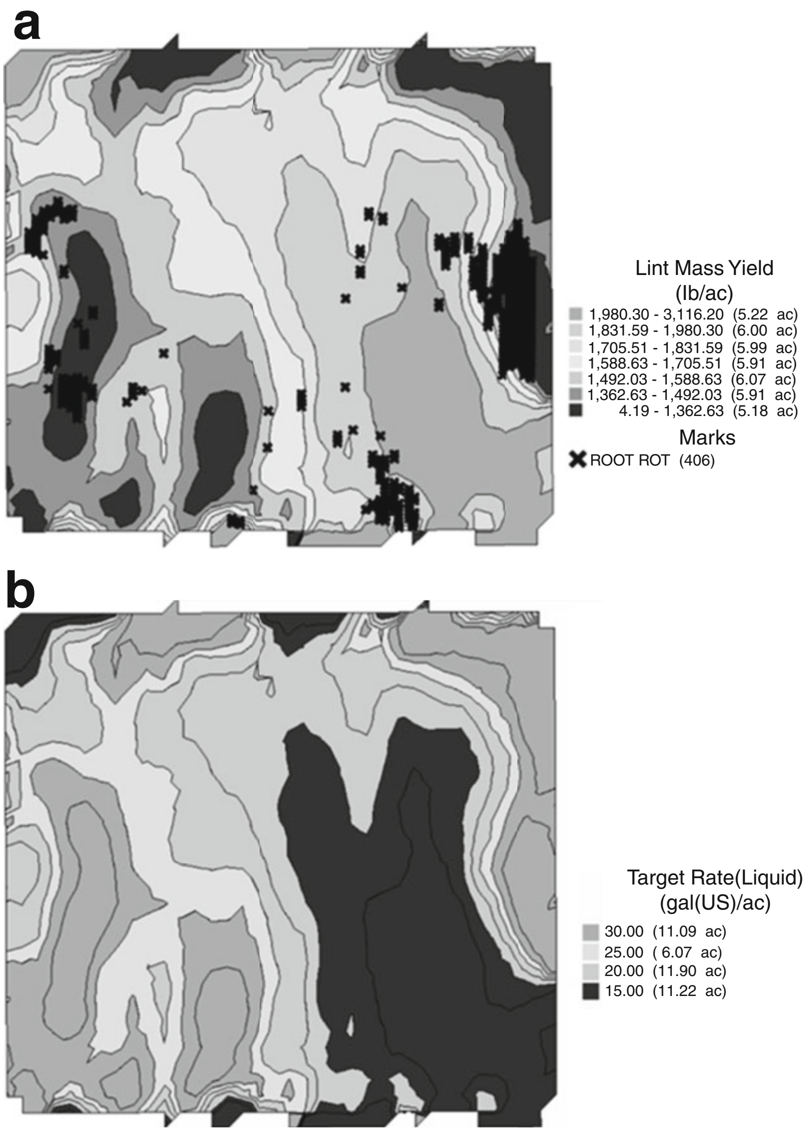

Fig. 17.3 (**a**) Cotton lint yield map of the experimental area of 2003, (**b**) Prescription map prepared for 2004 based on yield map of 2003 (Source: Norton et al. 2005)

in a grid format with smoother transitions. In this method, the VR presence of GPS helps to locate the machine in the field. According to the location and prescription map, a desired quantity of input is applied. A typical prescription map is shown in Fig. 17.3. Norton et al. (2005) generated a prescription map for variable rate application of P fertilizer application in cotton crop. Cotton lint yield map from a

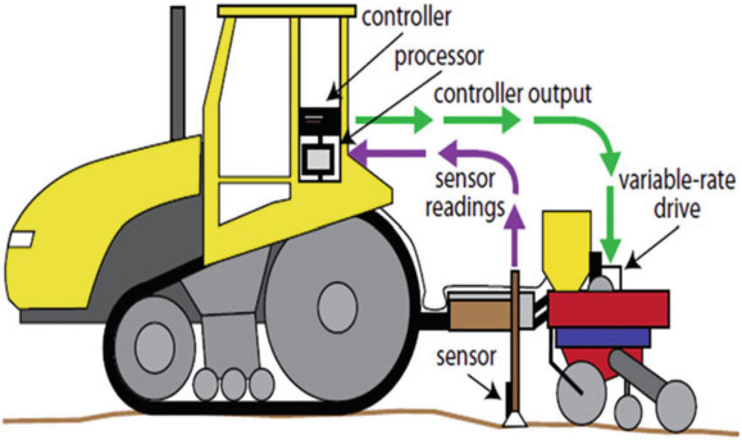

Fig. 17.4 An ideal sensor-based VRA application system (Source: Ahmad and Mahdi 2018)

cotton picker-mounted yield monitoring system was collected during 2003. Based on the lint yield map, the experimental site was divided into 7 yield zones and a prescription map was generated using this yield map. The zones of low lint yield received a higher rate of liquid P fertilizer than the zones of higher lint yield.

Site-specific aerial application of farm inputs is gaining popularity. The integration of aerial VRT and remote sensing can save a lot of time and cost of application. (Yang and Martin 2017) integrated these technologies for site-specific weed management. They used IntelliStar variable-rate aerial application system and airborne multispectral imaging system. Natural color and NIR aerial images were acquired in the fallow field just before weedicide application. These images were rectified and classified for weeds. Binary prescription maps were generated and glyphosate was sprayed using aircraft-mounted variable-rate applicator in infested areas and non-infested areas. Post application assessment was carried out with aerial images acquired at 14 days and a prescription map. Their results showed that imaging systems and variable rate applicators of weedicides were helpful in the effective control of weeds in the field.

B. *Sensor based*: In sensor-based approach of VRA, crop and/or soil properties are measured by a sensor in real-time as the applicator moves across the field. The onboard computer send signal to the rate controller by processing and interpreting data collected by the sensor. A predetermined algorithm is directly converted to an application rate using the sensor information. One limitation of this approach is that the rate controller needs to respond quickly because the prescribed rate changes with the moving of the applicator across the field. A sensor-based VRA system consists of three main components (Fig. 17.4): (1) sensor component, (2) Onboard processor for computations, and (3) variable-rate drive. The sensor records the variability information and the processor uses this information to send signals to variable-rate drive for variable rate application.

17.4.1 Application of Fertilizers and Pesticides Using VRA

Nitrogen (N) fertilizers are consumed in large quantities all over the world, however, its efficiency varies between 25 and 50%(Sharma and Bali 2017). It indicates that more than 50% of these fertilizers applied in arable lands are subjected to wastage through leaching and volatilization, etc. Therefore, improving N uptake by plants is a solution, or need-based application is the best solution for improving efficiency. Tekin (2010) conducted a study to examine the economic benefits of VRA in Turkish wheat production and found that application of N fertilizer based on soil variability resulted in 1–10% increase in yield with 4–37% saving of fertilizer. (Q. U. Zaman et al. 2005) measured citrus plant canopy size in 17 ha grove with an automated ultrasonic sensor system coupled with Differential Global Positioning System (DGPS) to prepare the prescription maps. Two plot scale and a field-scale experiment were conducted by (Evangelou et al. 2020) in central Greece to evaluate the effectiveness of in season VRA of granular N fertilizer to maize. Crop canopy condition was assessed using a single Crop Circle ACS-430 active canopy sensor interfaced to a GeoScout X data logger at 6–7 leaves stage of the crop. This sensor operated in three optical channels at 670 nm (red), 730 nm (red edge), and 780 nm (NIR). These channels were used to calculate NDVI and NDRE for plot scale and field-scale experiments based on plant vigor. A reference VI value was considered based on the literature (Holland and Schepers 2013), above which plants are considered non-N limiting. These vegetation indices were used for spatial variability detection, and N application rate was computed using an algorithm. Their results revealed that the algorithm computed 34 and 51% less N requirement than conventional practice without any yield sacrifice in the plot scale experiments, whereas it computed 34% less in season N or 24% less total N than farmer rate with any loss in yield in the field-scale experiment. As a result of the reduced application of N and no yield loss, VRA improved agronomic N use efficiency by 21–30% and decreased soil nitrate levels. Van Evert et al. (2012) found that 33–50% of herbicides were saved when ground-based and remote sensing derived weighted difference vegetation index (WDVI) based techniques were used to apply herbicide in the field.

17.5 Estimation of Soil Properties Using Remote Sensing Techniques

The estimation of soil properties is important for many applications such as soil classification, land use planning, soil mapping, and soil surveying (Morrisette et al. 2009; Meena et al. 2020). Conventional soil mapping methods can be achieved through in-situ assessment which includes soil surveying, soil classification followed by laboratory analysis which involves field soil sampling and analyzing soils for physic-chemical parameters using standardized laboratory methods (Yadav et al. 2020). Over the past few years, soil scientists used well-known conventional laboratory methods to define the temporal variability of soil properties. However, there are limitations of conventional methods with regard to meeting the high demands of detailed soil information in short time with reasonable cost and rapid assessment (Stenberg et al. 2010). Remote sensing has emerged as a promising alternative technique due to its advantages such as it does not require the use of chemical reagents to quantify soil properties. It can provide detailed information about soil variability rapidly without disturbing the soil, and cover large areas with high accuracy depending on the resolution of the sensor. The information about soil may be revealed by remote sensing since the signals measured are related to the physical measures that can be linked to soil properties. The advantages of using remote sensing techniques include the non-requirement of chemical reagents, lack of disturbance to the soil, and simultaneous estimation of various soil properties using a single spectrum from remote sensing spectral data.

17.6 Use of Multispectral Images to Estimate the Soil Properties

Liao et al. (2013) demonstrated that there is a significant relationship between soil texture (sand, silt, and clay content) and Landsat ETM reflectance of six bands from visible to an infrared portion (bands 1 to 5 and band 7), but the higher correlation was with band 7. Ahmed and Iqbal (2014) explored the potentials of RS and GIS techniques in studying the spatial variability of surface soil attributes. They collected 170 surface soil samples from Shorkot Tehsil in Punjab (Pakistan) and these samples were analyzed for soil texture and organic matter. It was found that bands 4 and 6 of the Landsat TM5 satellite were the best predictors of percent silt and clay, whereas organic matter was best predicted by bands 1, 6, and 7 using multivariate linear regression (MLR). Zhou et al. (2020) compared boosted regression trees, random forest, Bagged CART, and support vector machine to estimate organic carbon and total nitrogen in soils of the southern part of Central Europe using digital elevation model (DEM) derivatives, multi-temporal Sentinel-1, and Sentinel-2 data. They found that boosted regression trees model performed better than the other three methods. Multi-source sensor methods provided accurate predictions of organic carbon and total nitrogen contents than individual sensors. Setia et al. (2013) used the paddock by paddock approach to estimate soil salinity at farm level in parts of South Australia using the pan-sharpened four-band multispectral imagery.

17.7 Use of Hyperspectral Data to Estimate Soil Properties

Nowadays, scientists have shifted their focus towards reflectance spectra within visible and near-infrared (Vis-NIR) regions of the electromagnetic spectrum to estimate soil attributes (Volkan Bilgili et al. 2010; Viscarra Rossel et al. 2011; Wenjun et al. 2014; Shaddad et al. 2016). The information about soil properties is derived by studying the interaction between incident radiation and soil surface (Islam and Karim 2019). The Vis-NIR spectra are influenced by the chemical composition and physical structure of the soil constituents. The main soil chemical and physical components that interact with electromagnetic radiation within the

Vis-NIR range are called Chromophores (a parameter or substance either chemical or physical that significantly affects the shape and nature of a soil's spectral reflectance) (Ben-Dor and Banin 1995). Organic matter, water, primary minerals (such as feldspar and carbonate), clay minerals, iron oxides, and salts are some of the main soil parameters that have been predicted in soils of the world using Vis-NIR spectroscopy (O'Rourke et al. 2016). Apart from soil chemical components, physical properties of soil such as aggregate size, and particle size distribution may have an influence on the spectral measurement due to radiation scattering or reflection. These parameters contain chemical bonds or functional groups (such as C-H, NH, S-H, and O-H) which are spectrally active. The near-infrared spectrum results from the weak overtones and combinations of fundamental vibrational bands and these bands occur when incident radiation energy interact with the chemical bonds in the molecules of soil constituents in the mid-infrared region (Zornoza et al. 2008). The visible spectrum is mainly influenced by electronic transitions of iron oxides which are caused by high incident radiation energy (Chang et al. 2001). The overtones, stretching vibrations, and combinations of these fundamental vibrational bands make it possible to characterize soil properties using reflectance spectra of NIR region. Ben-Dor and Banin (1995); Stenberg et al. (2010); Viscarra Rossel et al. (2011); Xu et al. (2017) reported that soil properties such as organic matter, total nitrogen, soil moisture, and clay had known spectral signals since these are composed of functional groups (N-H, C-H, C-H, and O-H). These soil properties have direct spectral absorption features in the visible and near-infrared region which make it possible to estimate their contents in soils accurately. Multivariate calibration techniques are recommended for quantitative analysis of visible and near-infrared spectra in relation to soil properties since the direct interpretation of Vis-NIR spectra is difficult due to overlaps of weak overtones and fundamental vibrational bands (Vågen et al. 2006). Analytical spectral device (ASD) field spectroradiometer and diffuse reflectance spectroscopy (DRS) Spectroradiometer are generally used to measure the reflectance from the soil surface (Chacón Iznaga et al. 2014; Gandariasbeitia et al. 2017). Zornoza et al. (2008) evaluated the ability of near-infrared (NIR) reflectance spectroscopy to estimate various physical, chemical, and biochemical properties of soils and they reported good prediction of exchangeable calcium, magnesium, and water holding capacity of soils using NIR spectra. However, pH and exchangeable phosphorus were poorly predicted in soils. Paz-Kagan et al. (2015) suggested that airborne image spectroscopy can be used for estimating soil properties with good accuracy. Wenjun et al. (2014) compared in-situ measured soil properties with laboratory-based spectra using Vis-NIR spectroscopy, and they found that organic carbon, total nitrogen, and available nitrogen can be quantitatively predicted with various accuracies while available phosphorus and available potassium can be poorly predicted with laboratory-based visible and near-infrared spectra. Chacón Iznaga et al. (2014) found that organic matter and available phosphorus can be estimated from model visible and near-infrared spectra using a support vector machine. Qi et al. (2017) found that linear multi-task learning models performed better than partial least square regression (PLSR) in predicting soil properties. Viscarra Rossel et al. (2011) compared the simultaneous estimations of various soil constituents in three regions of the electromagnetic spectrum (visible, near-infrared, and mid-infrared, respectively) and also the combined spectrum (Vis-NIR-MIR) using partial least square regression (PLSR). Zhang et al. (2013) compared the ability of laboratory-measured spectra and Hyperion image spectra to predict soil moisture, total carbon, total phosphorus, total nitrogen, and clay content. They found that partial least square regression can predict all soil constituents using laboratory spectra while Hyperion reflectance spectra only gave good prediction for total carbon and total nitrogen. These results suggest that spectral resolution had impacts on the PLSR performance in predicting soil constituents. Zhang et al. (2013) used the imaging spectroscopy to predict soil constituents taking into account the fractional vegetation cover and found that the prediction performance of model for clay, sand, and CEC using spectral data from airborne sensor were satisfactory. (Mallah Nowkandeh et al. 2018) predicted organic matter in soils from Hyperion image using PLSR, principal component regression (PCR), Minimum Regression (MinR), and stepwise regression (SWR) and they found a good prediction accuracy of soil organic matter with PLSR and SWR than the other methods. Sentinel-2 and Landsat-8 satellite images with bare pixels were found to be suitable to map soil properties such as soil color, clay, sand, silt, and organic matter content (Silvero et al. 2021). Gomez et al. (2019) showed that Seninel-2 data can be used to estimate soil texture. Zhou et al. (2020) used Landsat-8, Sentinel-2 and Sentinel-3 to predict soil organic carbon content and C:N ratio using different machine learning techniques such as boosted regression tree, support vector machine and random forest at different spatial resolutions (20 m, 40 m, 400 m, 800 m). The SCLM technique can be used to reduce the influence of soil color during the development of prediction models. Hyperspectral imagery data was compared with laboratory visible-NIR spectral data by Hong et al. (2020). They used competitive adaptive reweighted sampling and random forest to develop the models to for soil organic carbon and found that laboratory spectra were better than hyperspectral imagery data.

17.7.1 Soil Moisture

Soil moisture has a significant role in regulating the water cycle and it has been listed as an essential climate variable by GCOS-WMO (Global Climate Observing System-World Meteorological Organization). Soil moisture is highly varying both spatially and temporally. It is a difficult task to measure soil moisture on a regional scale. Remote sensing techniques provide soil moisture data to some extent with lesser accuracy and precision is compromised. Optical and thermal remote sensing data (Sentinel-2, Landsat and MODIS, etc.) can be used to retrieve soil moisture from 10 to 250 m spatial resolution but it is mostly affected by cloud cover and other atmospheric disturbances. On the other hand, microwave remote sensing data (Sentinel-1, ALOS-2/PALSAR-2, SMAP, SMOS, etc.) provides all-time all-weather data but it is affected by surface roughness and soil texture, etc. There are several approaches for retrieving soil moisture from satellite data at different spatial resolutions and scales (global, regional, and local). Foucras et al. (2020) fused the

Sentinel-1, Sentinel-2, and MODIS data to derive the soil moisture at 500 m spatial resolution and 6 days temporal resolution in South of France, Western Benin, Central Tunisia, and South-western Niger. They derived soil wetness index ranging from 0 (driest) to 1 (wettest) using change detection method, seasonal condition, and vegetation densities. Their results were well correlated with in-situ measurements and existing satellite-derived data (ASCAT). Although L-band radiometer data is found to be most reliable for deriving surface soil moisture (0–5 cm depth), spatial resolution (at km scale) fails at capturing detailed variability (Piles et al. 2014). Using machine learning techniques like Regression Tree, Artificial Neural Network, and Gaussian Process Regression, Senanayake et al. (2021) downscaled soil moisture based on soil thermal inertia over the semi-arid agricultural landscape in Australia. Their results showed low RMSEs compared with airborne and in-situ measurements. Multi-sensor multi-resolution approach for deriving soil moisture can be helpful in filling the gaps. Senanayake et al. (2021) used Landsat-8 and Sentinel-2 data of similar dates to derive soil moisture at 30 m and 20 m, respectively. Thermal band (Landsat-8), SWIR band (Sentinel-2), red and NIR (Landsat-8 and Sentinel-2) based soil moisture were derived by downscaling the CCI and SMAP soil moisture data for a small area in Jharkhand (India), and the SWIR based soil moisture was found to be accurate as compared with others bands.

17.7.2 Detection of Abiotic and Biotic Stresses in Crops

Remote and proximal sensing is useful for identifying abiotic and biotic stresses in crops. Plant stress is characterized as a significant change from ideal conditions during crop growth that could add negative impacts on crop growth. Biotic stresses (pests and diseases) and abiotic stresses (like nutrient deficiency, water stress, salinity, etc.) cause serious economic losses (Oerke 2006). The identification of spots with pest or disease activity facilitates the farmer to apply the right amounts of insecticides and pesticides to the affected areas which may be helpful for environmental and economic purposes (Datt 2006).

The earth observation data with optical sensors have been used to detect biotic and abiotic stresses in crops. Physical and physiological changes for the reflectance of visible and near-infrared radiation from vegetation have been extensively (Knipling 1970). In general, stress causes an increased reflectance in the visible region due to decreased chlorophyll in stressed plants leading to decrease in absorption of visible light, and a decreased reflectance in the NIR region due to changes in internal leaf structure, leaf morphology, and internal heat temperature (Hatfield et al. 2008). Reflectance and absorption energy at important band wavelengths are altered by these biotic-abiotic factors interfering with photosynthetic activity and physical structure of plants (Moran et al. 1997). For understanding the spectral contributions of vegetation to multispectral observations, vegetation indices with their mathematical transformations are beneficial. The list of important vegetation indices to detect the abiotic and biotic stresses in crops is given in Table 17.1.

Table 17.1 Spectral indices to detect abiotic and biotic stresses in crops

S. No.	Index	Formula	References
1.	Normalized difference vegetation index (NDVI)	(R800 − R670)/(R800 + R670)	Rouse et al. (1974)
2.	Red edge position (REP)	700 + 40(RRE − R700)/(R740 − R700) RRE = (R670 + R780)/2	Baret and Guyot (1991)
3.	Chlorophyll index (CI)	(R415 − R435)/(R415 + R435)	Barnes et al. (1997)
4.	Photochemical reflectance index (PRI)	(R531 − R570)/(R531 + R570)	Gamon et al. (1992)
5.	Normalized pigment chlorophyll index (NPCI)	(R680 – R430)/(R680 + R430)	Penuelas et al. (1995)
6.	Structure insensitive vegetation index (SIPI)	R(800 − R445)/(R800 + R680)	Penuelas et al. (1995)
7.	Red-edge vegetation Stress index (RVSI)	(R714 nm + R752 nm)/2 − R733 nm	Merton and Huntington (1999)
8.	Modified chlorophyll absorption reflectance index (MCARI)	[(R700 – R670) − 0.2 (R700 – R550)] (R700/R670)	Daughtry et al. (2000)
9.	Transformed chlorophyll absorption reflectance index (TCARI)	3 [(R700 – R670) − 0.2 (R700 – R550)(R700/R670)]	Haboudane et al. (2008)
10.	Anthocyanin reflectance index (ARI)	(R550) –1 – (R700) –1	
11.	Water index (WI) Disease water stress index-2 DWSI-2	R900 nm/R970 nm R1660/R550	Penuelas et al. (1995)
12.	Normalized difference nitrogen index (NDNI)	(NDNI = [log (1/R1510) log (1/R1680)]/[log (1/R1510) + log (1/R1680)])	Serrano et al. (2000)
13.	Normalized difference lignin index (NDLI)	(NDLI = [log (1/R1754) log (1/R1680)]/ [log (1/R1754) + log (1/R1680)])	Serrano et al. (2000)

Indian satellite series IRS Linear Imaging Self Scanning (LISS) -III and LISS-IV sensors can be beneficial with high spatial resolution in precision agriculture and crop monitoring (Dadhwal et al. 2006). The series of Landsat sensors have 30 m pixels, and there is a range of upcoming satellites such as QuickBird and IKONOS that have less than 1 m spatial resolution. RapidEye, is now available with 5-m spatial resolution equipped with a red-edge band which helps to understand the regions where abiotic-biotic stresses in crops are prominent (Santoso et al. 2011).

17.7.3 Detection of Abiotic Stresses in Crops Using Remote and Proximal Sensing

Plant reflectance spectra are influenced by biochemical components (Buschmann and Nagel 1993; Baret et al. 1994). The detection of water stress and nutrient deficiency in crop canopies at the early stages of crop growth is required to increase the efficiency of inputs required for crop production. Reflectance and absorption features in narrow-bands of hyperspectral remote sensing are related to specific crop physical-chemical traits such as water content, plant ecophysical status, biochemical composition, morphology, and physical structure (Strachan et al. 2002).

The Impacts of nitrogen usage and chlorophyll pigment concentrations also affect the radiation from the source is reflected, absorbed, or transmitted (Lillesand and Kiefer 1979; Carter 1994). One specific index for chlorophyll estimation is the Chlorophyll Absorption ratio index (CARI) which measures the depth of concentration at 670 nm relative to green reflectance where it is observed rising at 550 nm, and its reflectance dipping at 700 nm, The ratio of reflectance at 550/700 nm is constant for leaf-level regardless of leaf chlorophyll concentration (Kim et al. 2011). Modified chlorophyll absorption ratio index (MCARI) was obtained from CARI which is less sensitive to chlorophyll effects but more responsive to green LAI variations and more resistant to background effects, soil, and atmospheric effects (Daughtry et al. 1992). Narrow hyperspectral bands measure exact characteristic absorption peaks of plant pigments and provide better information about plant health (Muhammed 2005). Nitrogen concentration can be determined by band-band ratios (band r^2) where leaf reflectance ratios between wavebands in red-edge (700–716 nm) and a waveband in NIR (755–920 nm) provided a good prediction of leaf N concentration in wheat and maize crops (Tarpley et al. 2000). Xue et al. (2004) found that NIR to green ratio ($R_{810/}$ $_{R560}$) had a linear relation with total N concentration, irrespective of the growth phase of wheat and cotton.

The effects of macronutrients (such as phosphorus and potassium) can be differentiated between healthy and stressed crops using NIR and blue spectral wavelengths(Osborne et al. 2002). Absorptions at 830, 940 and 1100 nm were lower for phosphorus and calcium deficient maize leaves, whereas the leaves deficient in sulphur, magnesium, potassium, and nitrogen had higher absorption at these wavelengths (Al-Abbas et al. 1972). The effects of biochemical constituents (such as lignin and cellulose) on spectral reflectance can be explained due to the presence of O-H and C-H molecular transitions. Panigada et al. (2014) investigated the usefulness of narrow-band multispectral remote sensing techniques and thermal imagery for water stress detection in cereal crops. (Suárez et al. 2009) used the high-resolution multispectral imagery for the remote detection of water stress via a physiological index (Photochemical Reflectance *Index*, PRI). They found that this technique is a viable option for irrigation scheduling of orchard crops. Taghvaeian et al. (2014) used the two spectral indices (crop water stress *index*, CWSI, and Degrees Above Non-Stressed Canopy, DANS) based on remotely-sensed canopy temperature to monitor the water stress in sunflower grown in northern Colorado. According to (Yazar et al. 1999), the CWSI is a useful spectral index for evaluating crop water stress in corn and this may assist in decision making about irrigation of crops.

Hyperspectral imaging can detect the small changes in physiology and biochemistry of crops caused by nutrient deficiency or other stress factors (Datt 2006). Normalized total pigment to chlorophyll-a ratio index (NPCI) was significantly correlated with total chlorophyll concentrations in plants to know the response of N-concentration in crop phenology. Low attitude flights equipped with hyperspectral sensors usually have a high spectral and spatial resolution which is helpful in detecting the stresses in crops. Many studies have used hyperspectral remote sensors such as hyperspectral mapping (HyMap), Airborne Visible Infrared Imaging Spectrometer (AVIRIS), and Compact Airborne Spectrographic Imager (CASI) for site-specific nutrient management (Zhang et al. 2008). Disease Water Stress Index (DWSI) was formulated particularly for water stress determination for sugarcane crops in Australia (Brunini and Turco 2018). The severity of stress in mustard and wheat crops was determined by Datta et al. (2008) using DWSI with Hyperion EO-I data.

17.7.4 Detection of Biotic Stresses in Crops

Multispectral airborne imagery has been used for detecting different kinds of diseases like identifying Phytophthora footrot in Citrus trees (Wang et al. 2019) root rot in cotton (Wang et al. 2019), and late blight in tomatoes (Zhang et al. 2006). QuickBird satellite data was used to monitor the rust in wheat (Franke J), basal stem rot in oil palms (Venkateswarlu et al. 2012). Multispectral remote sensing data acquired from sensors in Visible and NIR bands are found to be prominent to detect disease of rice sheath blight (Tong et al. 2014). Besides multispectral remote sensing, hyperspectral remote sensing has been used to detect the biotic stresses in crops. Ray et al. (2010) used an airborne visible infrared imaging spectrometer (AVIRIS) image for identification of diseases in tomatoes from stage 1 (low symptom) to stage 4 (severe damage). The difference in healthy and diseased potato plants was noticed in the range of 770–860 nm and 920–1050 nm (Ray et al. 2011). Thermal remote sensing has also been proved efficient in detecting diseases and pathogens in plants by analyzing the temperature difference between infected and non-infected leaves which may help in the pre-symptomatic diagnosis of diseases and pests in plants. Oerke (2006) has used thermal infrared to detect a disease in cucumber called *Pseudoperonospora cubensis* that causes downy mildew. Stoll et al. (2008) have shown the usefulness of thermal imaging in irrigated and non-irrigated grapevine as the thermal infrared band helps to detect the pathogens before their actual physical visibility on plants.

17.7.5 Unmanned Aerial Vehicles for Crop Production

Remote sensing can be used to derive various parameters for predicting and monitoring crop damage, crop yield, soil moisture, soil texture, etc. Space-borne remote sensing has proven capable for local, regional, and global scales but for agriculture needs, farm or plot scale monitoring is required. Currently, the use of drones or UAVs (Unmanned Aerial Vehicles) has become popular especially for precision agriculture. Drones carry sensors at low altitudes compared with space-borne sensors. It can differentiate field level changes of crops resulting in much more detailed vegetation analysis in red and NIR regions. Multispectral, hyperspectral, thermal, and LiDAR sensors can be mounted on drones and can acquire data in all these EM regions. Drones along with wireless sensor networks are also used for controlled spraying of pesticides over farmlands (van der Merwe et al. 2020). Using high-resolution imageries from drones, plant germination level scans also be monitored, and necessary action can be deployed (Sankaran et al. 2015). Weed detection mapping (Sankaran et al. 2015), water level management (Gago et al. 2015), and crop damage assessment (Puri et al. 2017) are few other important applications in agriculture using UAVs.

17.8 Conclusions

Remote sensing and GIS are useful in the generation of information for various components of agricultural systems. The satellite data helps in the assessment of crop growth stages and conditions, which can then be used to derive the information on are, production, and yield. Multi and hyperspectral imagery has been used to characterize abiotic and biotic stresses in crops over the years, but hyperspectral data and imagery have greater details than multispectral imagery. This may help in better understanding the crop stress caused by nutrient deficiency and water-stressed conditions. The farmers generally apply inputs uniformly without accounting for spatio-temporal changes, which results in environmental, economic, and nutritional losses. The situations can be altered by developing field-scale-soil-sensing technologies, and site-specific digital spatial repositories for precision farming applications. Since the big geospatial data has been increased exponentially over the years, modeling and simulation of geospatially enabled data require high-performance computing coupled with data analytics and machine learning techniques.

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Plans and Policies Towards the Input Use Efficiency for Food and Environmental Security

18

Ganesh Chandra Banik and Dibyendu Mukhopadhyay

Abstract

Continuous growth in population and food demand are the major challenges for most of the countries to ensure food and environmental security for their citizens. Globally, the number of people suffering from food insecurity and hunger are no longer declining, rather it is increasing slowly in last few years. It is concerned that the number of hungry people would surpass 840 million in 2030 from today's 690 million. Keeping in abeyance the other factors responsible for global hunger such as economic downturn, social and economic conflict, climate change and environmental degradation, etc., current food production needs to be doubled to meet the demand and achieve "zero hunger" postulated by United Nations by 2030. Increasing the rate of current food production require heavy use of various agricultural inputs. Limited availability of natural resources for food production forced the farmers to depend on artificial inputs like fertilizers, agro-chemical, etc., which are also creating havoc for the environment. Indiscriminate use of agri-inputs is not desirable from the environment point of view. Increasing input use efficiency is the only option to increase the food production in sustainable manner without hampering the surrounding ecosystems. Several measures have been taken at national and international levels to develop and execute specific plans and policies to increase input use efficiency and conserve natural resources as well as soil and environmental health. Attempts have always been taken to

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produce more food with limited use of land, labour, seeds, fertilizers, pesticides, etc. However, the proper implementation of the plans and policies require periodical evaluation, monitoring and necessary upgradation to maintain projected growth of agricultural production. Strategic measures are expected to be taken for strengthening the existing policies for sustainable and environment friendly agri-input system.

Keywords

Food security · Agricultural inputs · Input use efficiency · Plan and policies · Environmental degradation

Abbreviation

SDG	Sustainable Development Goal
UN	United Nations
FAO	Food and Agriculture Organization
FSIN	Food Security Information Network
NUE	Nutrient Use Efficiency
N	Nitrogen
P	Phosphorus
K	Potassium
PPP	Public–Private Partnership
ICT	Information and Communication Technology
RCT	Resource Conservation Technology

18.1 Introduction

Food is the fundamental need to human well-being, and achieving food security is a prerequisite for human development. Providing safe, sufficient and nutritious food for all people to ensure global zero hunger is one of the 17 sustainable development goals (SDGs) adopted by the United Nations (UN) as a part of its 2030 agenda of sustainable development to eradicate inequality from the globe leaving no one behind (UN 2015). Assurance of food security is not just to increase the food production, rather it exists *when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life* (FAO 1996). Household food and nutritional security is the application of this concept to the family level to ensure food security to all individuals living in each household (FAO 1996). Food security is determined by four factors, such asavailability, stability of supplies, access, and utilization of food (Poppy et al. 2014) (Fig. 18.1).

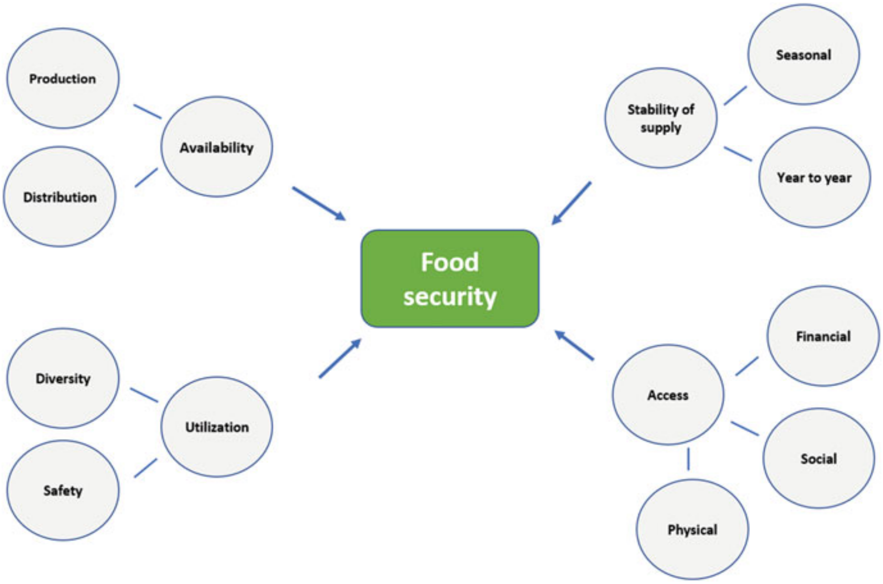

Fig. 18.1 Schematic of the factors of food security

Ensuring global food and nutritional security and development of sustainable food systems are two major challenges for the policy makers in the agricultural system (Bilali et al. 2018). Yet despite increase in global food production after green revolution approximately one billion people around the globe do not have access to enough food to eat today, and a further billion lack proper nutrition (Pinstrup-Andersen 2009; IFPRI 2016). The under-nourished peoples are mainly located in the low-income developing countries (IEG 2011) while more than one billion people in developed nations are sufferings from obesity (Swinburn et al. 2011; Kumar et al. 2018). Continuing increase in global population next 50 years, coupled with economic, social and other associated pressures, may elevate global food demand still higher (Godfray et al. 2010). An estimated overall rise of 70% food production between 2005/2007 and 2050 is required to feed about 9 to 10 billion people in 2050; whereas for developing countries, production needs to be almost doubled (Alexandratos and Bruinsma 2012; UN 2015). Demand for cereal grains, for both human and animal feed is predicted to raise to about 3 billion tons by 2050 from today's around 2.1 billion tons. According to the 2019 edition of the Global Report on Food Crisis (GRFC) of Food Security Information Network (FSIN 2019) more than 113 million people in 53 countries have suffered from acute hunger and thus required urgent food, nutrition and livelihoods support in 2018. There was little improvement from the report of 2017 which estimated that 124 million peoples were suffering from acute hunger in 51 countries (FSIN 2018). Among them some 74 million people, two-thirds of the total resided in 21 countries and territories. About 33 million hungry people resided in 10 countries in Africa; over 27 million hungry people were in seven countries and territories in West Asia/Middle East; 13 million were in three countries of South/South-East Asia and 1.1 million people in eastern part of Europe. According to the order of hunger approximately 72 million people were located in eight countries namely Afghanistan, Democratic Republic in Congo, Ethiopia, Yemen, northern Nigeria, Syrian Arab Republic, Sudan, and South Sudan. As per FSIN (2019) report the causes of such crisis were lied in social conflict, social insecurity, natural disasters, climatic shocks, and also in economic turbulence present in different developing countries. Most of the undernourished people live in rural areas and depend on agriculture for their livelihood. Not only the lack of enough food, the micronutrients such as iron, iodine, zinc as well as vitamin A related malnutrition (commonly called as "hidden hunger"') are affecting nearly 2 billion world population, which is approximately about one third of the total global population (UN 2012; Bioversity International 2014).

Although agricultural food production system has changed very much over the last 50 years, sufficient food production in a sustainable manner to meet the growing global demand is one of the greatest challenges in this twenty-first century (Tilman et al. 2002). Because of the green revolution in 1960–1970s, there was rapid advance in agricultural input technologies not only in industrial countries but also in the developing world (Pingali 2012; Kumar et al. 2021). The resultant rapid increase in agricultural production has decreased the hunger worldwide (Godfray et al. 2010; Mehta 2018). Current food production is assumed to be sufficient to meet the global demand (Lee et al. 2018), but still the food insecurity persists in terms of large differences between countries, even within the same country (FAO 2002; FAO, IFAD and WFP 2015). The problem is more aggravated to some extent due to wastage of food as well as non human use of agricultural food products such as maize as the animal feed. The varied dietary preferences are also an important aspect for achieving global food security in 2050 (Godfray et al. 2010; Kastner et al. 2012; Liu et al. 2020). Substantial growth is required in food production within the next three decades to meet the growing needs of human as well as the livestock (FAO 2009; Tilman et al. 2011; Alexandratos and Bruinsma 2012).

Efficiency in use of agricultural inputs such as land, labour, fertilizers pesticides, water, seed, etc., shall play the most pivotal role to increase the food production in next decades. Sustainable increase in food production requires free and fair access to all types of inputs and also a balanced distribution of low-cost resource availability (Bilali et al. 2018). Use of modern fertilizers and pesticides after the green revolution have accelerated the agricultural production and yield. However, the pursuit for ensuring food security through increased agricultural production by heavy use of inputs may result negative impact to the environment (UNEP 2011).

Excessive application of agricultural inputs may result in environmental changes ("global environmental change" – GEC) which include effect on climate; land, water, air and ecosystem degradation; and pollution; loss of biodiversity; excessive greenhouse gas emissions; loss of tropospheric ozone; rise of sea level; accumulation of heavy metals such as arsenic, lead, cadmium, chromium etc. (Gregory and Ingram 2000; GECAFS 2015; WWW-UK 2013; FAO, IFAD and WFP 2015; Udeigwe et al. 2015; IUCN 2016; Bilali et al. 2018). It is estimated that the agricultural activities occupy 40% of Earth's land surface which is far more than any other human activity. It also accounts for >70% of freshwater withdrawals for irrigation and it directly contribute to 10–14% of the global anthropogenic greenhouse gas emission (Francesco et al. 2013; Tubiello et al. 2014; Clark and Tilman 2017); Pressure of population growth is likely to aggravate these negative impacts in the next several decades (Bajzelj et al. 2014; Springmann et al. 2016).

The dependence of agriculture on inputs such as fertilizers, pesticides, land, water etc. to obtain and maintain sustainable high productivity and farmer's profit without affecting the surrounding environment seeks for comprehensive policy measurements. Such policies may include premium prices for products produced from eco-efficient systems or minimum support price and maximum subsidies in inputs. Policy measures for input subsidies, especially for fertilizer, seed and irrigation water, and output support price protection encourage the farmers to adopt the practices that would enhance input use efficiency and thereby, contribute to sustain agricultural resource base. However, periodical evaluation, necessary alteration and proper implementation of plan and policy measures may change farmers behaviour to accept more sustainable practices, e.g., withdrawal of pesticide subsidies led to a dramatic drop in insecticide use in 1990s in Indonesia (McIntyre et al. 2009). The policy measures provide incentives for development and stimulate the farmers for adoption of more diverse, eco-efficient farming. Policy intervention to adopt Environment Friendly Farming Practices (EFFPs) aimed to mitigate critical environmental issues (Mozzato et al. 2018) and may act as a tool to reduce the diffuse soil and water pollution and improve the ecological quality (Blazy et al. 2011). The policy incentives have driven the improvement of agricultural productivity with lower input used in developed countries to make the agriculture more sustainable and lower the damage to environment. Such incentives include innovation and adoption of better technologies for efficient input use, farm mechanizations, national support for organic agriculture, reduction in pesticide usage, nutrient regulation, participatory watershed management, conservation agriculture, and promotion for adopting cutting-edge modern technologies like biotechnology, information and communication technology, etc., in agriculture. The objective of this chapter to analyze existing plans and policies implemented for increasing input use efficiency and food production and to suggest strategic options to increase the agricultural production in sustainable eco-friendly manner.

18.2 Vision and Mission for Food and Environmental Security

Global agricultural system is passing through a rapid transformation due to the technological development. Production and productivity of cereals, pulses, oilseeds, etc., have been grown considerably in the last 60 years after green revolution (Kumar et al. 2021). But still a large number of people are suffering from poverty, inequalities, hunger, and malnutrition not only in the rural areas of the developing world but also in the urban areas across the globe. However, the world leaders at the UN Conference on Sustainable Development in 2012 in Rio de Janeiro (Rio + 20) reaffirmed the right of each and every one to have access to safe, sufficient, and nutritious food, consistent with the fundamental right to be free from hunger. But achieving the right to food security requires to overcome may economic, social, and political hurdles across the nations. The food and environmental security cannot be achieved without the human development and ensuring livelihood security. There are many aspects to be considered to achieve "food for all" in 2050.

18.2.1 Increasing Economic Growth

Economic growth and food security go hand-in-hand and are dependent on each other. The main cause of existence of hunger and malnutrition in the rural population of Sub-Saharan Africa, South -Eastern Asia and in Latin America is not always the unavailability of food, but sometimes inability to buy. Economic growth driven by growth in agricultural sector can reduce poverty and inequality in the rural peoples. Besides that, food self-sufficiency of a country not only saves foreign exchange but also encourage to produce food based on international trade trend and increases the diversity of the food produced.

18.2.2 Achieving Gender Equality

Gender inequality is a key challenge for ensuring food security and also for human development. There are few dimensions of gender inequality in the agricultural sector: land right, unpaid work, productive resources, employment, decision-making, and leadership, etc. (Sexsmith 2017). Gender inequality is a major reason for underperformance of agricultural sector in some countries. Although agriculture is providing employment to approximately 70% of women employed in Southern Asia and more than 60% of women employed in Sub-Saharan Africa, still they face more severe constraints than men in accessing productive resources, services, and marketing of farm products. This "gender gap" needs to be overcome to increase the productivity and achieve broad economic and social development goals. Guided by UN principle of "leaving no one behind" FAO 2030 policy on gender equality for achieving sustainable development prioritizes the equal participation and decision-making of men and women in rural institutions. Further, a positive correlation exists between gender and environment. Women are more active than men for resource conservation and restoration.

18.2.3 Intensification of Agricultural Production

Rapid population growth and small farm sizes call for innovation in agricultural practices to increase productivity from same piece of land. Sustainable agricultural intensification is projected to play key role in this regard to increase productivity without expanding the cropped area and other inputs. Technically, intensification of agriculture is defined as an increase in agricultural crop production per unit of input use. The inputs include land, labour, fertilizers, irrigation, etc. Such intensification facilitates saving the land for various other uses. It is widely necessary to meet projected food need in coming decades to maintain present dietary trend. Recently system of crop intensification using improved agronomic management practices has also been encouraged by the governments of a number of Asian and African countries to increase the crop production. For example, system of rice intensification (SRI) in India. Intensification of agriculture also helpful for environmental protection as it requires less inputs and also spare the land for other uses. More spared land emits less green-house gases and sequester more carbon (Robertson et al. 2000; Lamb et al. 2016).

18.2.4 Development of Green Economy

Green economy is resource-efficient and socially inclusive. Shifting towards a greener economy is required for environmental responsibility and social accountability in this present condition of population explosion and environmental degradation. Development of green economy system uses the renewable natural sources as inputs in agriculture and industrial sectors protecting environmental degradation without exposing our future generations to potential environmental risks and scarcities (UNEP 2011).

18.2.5 Development of Resilient and Sustainable Food System

Production of food and their distribution, both are human driven dynamic system which depends on economy, environment, ecosystem, and on a number of social institutions (Ericksen 2008). The present food system is intrinsically complex and include different steps, processes, value chains, and interactions (Tendall et al. 2015; Meena et al. 2020). Such complex system sometimes affects the stake holders as well as the consumers in multiple way and creates much uncertainty. Development of a resilient food system is an urgent need to feed 9 billion peoples in 2050. It is also necessary to develop production and consumption balance between local, regional and global levels in the food system.

18.2.6 Popularization of Organic Agriculture

Conventional agricultural practices use chemical fertilizers and plant protection measures, the residues of which have a great impact on food quality as well as on the environment. Organic agriculture nowadays is being promoted and popularized on global scale keeping in mind the health related concern of the consumers. Especially in the developed world it is true that people consider organically produced food be safer and healthier than conventional system. Organic farming practices require minimum use of off-farm inputs rather it restores and maintains the ecological harmony. Adoption of organic agriculture does not reduce the crop yield and it helps to maintain and nourish the sustainable agricultural production system without hampering the natural environment.

18.2.7 Using Water More Efficiently

Ensuring water security is prerequisite for achieving global food security. Fresh water is used for agriculture and it is a finite and venerable source. It was expected that water resources will be sufficient in global scale to produce the food required in 2050 but also warned about the substantial water scarcity in many regions (FAO 2015). Water shortage in different countries or in different regions of same country may increase the conflict which will constrain the agriculture. Optimizing the conjunctive use of rain and surface water is expected to enhance sustainability of agriculture particularly in the regions where the groundwater is overexploited. The necessary modification of cropping cycles, development of sprinkler or drip irrigation system, rainwater harvesting, etc., are few measures that may enhance the water use efficiency in coming decades with *motto* of “more crop per drop of water”.

18.2.8 Minimizing Yield Gap

Effective application of technological advancement coupled with farmer’s awareness and lab-to-land policy interventions decreased the yield gaps than that were in previous decades. However, still it exists and farmers are not capable to produce the optimum yield expected to be for a particular variety or crop. Further, the crop yield varies across the region even within the same agro-climatic zone. Large yield gap also persists between the yield obtained by small and marginal farmers in comparison to large farmers. The narrowing this yield gap require integrated and holistic approaches with financial support especially to the small-scale farmers. The management strategies such as increasing use efficiency of fertilizers, pesticides; soil management, land improvement; selection of location and weather specific variety; improving market access (Pradhan et al. 2015) may be useful.

18.3 Scenario of Input Use and Efficiency

Any production system either be agricultural or industrial is a continuous process, where some goods and services called “inputs” that are used to produce other goods and services called “outputs”. In agriculture, any external source that put into soil or used in agronomic management to help a farmer to increase crop yield is called input. The input can be anything from high-quality seeds to high-tech combined harvesters. There are endless agricultural inputs which can be divided into two categories; capital inputs such as land, tractors, etc., which require large investments and are non-perishable; while the second category is consumable inputs that are "consumed" by the crops such as seeds, manures, fertilizers, pesticides, irrigation, etc.

The efficiency of any input determines how much of input to be applied to get a certain yield and more the efficiency less the input needed. It is a simple measure of output or yield produced per unit area with a given amount of that input. Productivity can be increased either through use of more inputs and/or adoption of improved technology or by improving the input use efficiency at a given fixed level of inputs and available technology. An efficient farmer uses his land, labour, and other resources in optimal manner so as to maximize the yield of crop grown, i.e., increases the efficiency of input used. Use of modern inputs like improved seeds, fertilizers, pesticides, irrigation, etc., have expanded and sustained agricultural growth in different countries especially after the green revolution.

18.3.1 Land

Among the agricultural inputs land is considered as the most important household asset to support agricultural production system and provide for food, nutrition, and livelihood support especially for the rural peoples (FAO 2012). Demand for land is ever-increasing because of multiple land uses such as for cultivation, grazing, forestry, industrialization, habitation, etc. The global landuse system is facing a serious challenge due to population explosion, industrial bloom, spreading of urban sectors as well as also for the continuous climate change (Koondhar et al. 2016). The urban sprawl is thought to responsible for decrease of arable land in China (Long and Zou 2010) and other parts of world. In India, the urban expansion has decreased agricultural land by 16.31%. More than one third of the world's land surface is used as grassland (FAO 2016) whereas only 11.6% (1.5 billion hectare) is use for growing agricultural crops. In India 57% of total land is cultivated whereas in United states and China it is 17.1% and 13%, respectively. World bank data shows that per capita total arable land in India decreased from 0.233 ha in 1980 to 0.12 ha in 2016 whereas in China and United states the figures are 0.098 to 0.086 ha and 0.831 to 0.47 ha, respectively.

18.3.2 Water

Water is utmost essential for agriculture and allied sectors. Food production and livelihood security depend on the quantity and quality of water available. Agricultural production system is afraid to face serious problem for increasing water risks in the near future. In most regions of the world, over 80% of freshwater is used for agriculture. An estimated 15% increase in water withdrawals will be required by 2050 to feed a planet of 9 to 10 billion people. Global agricultural regions have been subjected to extensive and increasing water constraints (Khokhar 2017). For example, major droughts in United States and Chile have affected agricultural production

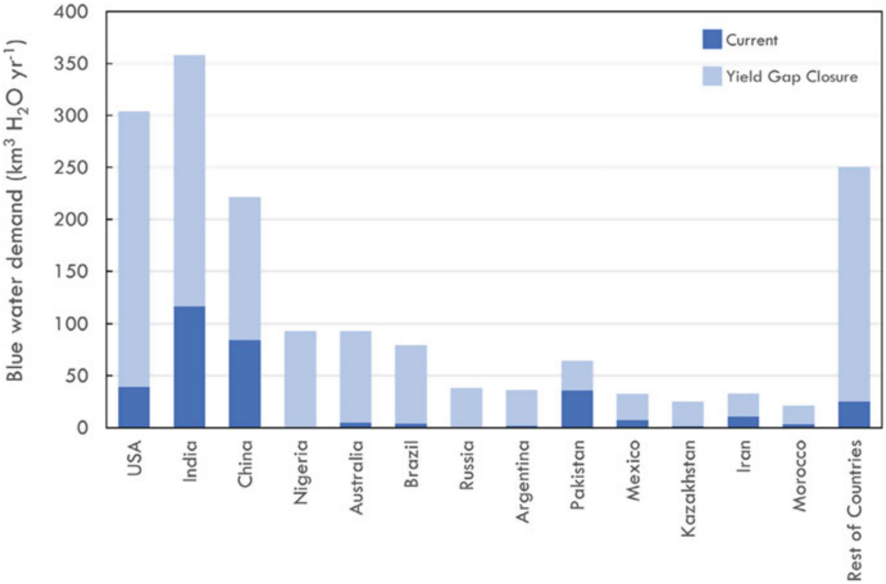

Fig. 18.2 Blue water required for crop production at yield gap closure. (Adapted from Davis et al. 2017 with permission)

and also diminished surface and groundwater reserves. Increase of global water scarcity resulted a decline of water availablity and shows a negative impact on agricultural production system despite about 95% of agricultural land are primarily rainfed (Hadebe et al. 2016). The yield of maize in china is decreased because of failure to meet the water requirements (Meng et al. 2016). According to Davis et al. (2017) about 146% increase in global irrigation water is required to maximise crop yield to feed the increasing population. Yield gap closure is strongly dependent on irrigation (blue water) in theregions affected by seasonal and/or chronic water scarcity (Fig. 18.2).

18.3.3 Labour

Labour is one of the most important input to increase and sustain the agricultural production especially in traditional non-mechanized system. It is now well established that the progress of the economic development and introduction of modern technologies and farm mechanization have reduced agricultural labour or the employment opportunities in the agricultural sector. Besides that, the progress of service sector is gradually replacing agriculture as the mainstay of employment fromyear 2000.But in the less developed nations agriculture is still the main bread earner for a large portion of population. For example, agriculture is providing 70–91% employment insome African countries such as Burundi, Somalia, Chad, Niger, Uganda, Mozambique, etc. In western European countries the figure is 0.96% in Belgium to 36.7% in Albania. In USA only 1.34% and in China 25.36% of workforce is employed in agriculture (www.theglobaleconomy.com/rankings/employment_in_agriculture/). India Economic Survey Report of 2018 showed that more than 50 per cent of the total workforce employed in India are involved in agriculture. A major portion of them are the "cultivators" and others are "agricultural laborer". It was also forecasted that the contribution of agricultural workers to total work force would drop to 25.7% by 2050 from 58.2% in 2001. A comparison study by Chand (2019) showed that role of agriculture in total workforce in last 25 years since 1991 has declined to around half in Brazil, China, and Malaysia. Labour share of agriculture in Vietnam declined by about 40 per cent and in case of it is one third.

18.3.4 Seed

Seed is indispensable for agriculture, either it be "local" or of improved quality. Small holder farmer of the developing world of South and South-East Asia, Sub-Saharan Africa, and Latin America lack the access of improved quality seeds. They rely on informal seed system which includes production, processing, storage, and reuse of seed for the next cropping season by the farmers. However, the global use of seed showed a compound annual growth rate of about 7% during 2011–2018 and reached to market value of USD 59.71 billion and predicted to reach to USD 90.37 billion in 2024 (Seed World 2019).

18.3.5 Major Fertilizers

Food and Agriculture Organization estimated that the global major fertilizer nutrient ($N + P_2O_5 + K_2O$) demand was about 184.02 million tons in 2015 and 186.67 million tons in 2016 (FAO 2017). It is expected to reach the worldwide demand to 201.66 million tons by the end of 2020 (Fig. 18.3) with the average annual growth of 1.9% in the following years. The demand for N, P_2O_5, and K_2O nutrients was expected to exhibit annual growth rate by 1.5, 2.2, and 2.4%, respectively from 2015 to 2020. While the International Fertilizer Association estimated that total 186 million tons of major nutrients were used in 2017 of which N, P_2O_5 and K_2O accounted for 57, 24, and 19%, respectively. Estimation of fertilizer nutrient use efficiency (NUE) measures how well plants use applied mineral nutrients from soil. Mineral fertilizer efficiency or NUE is a necessary precondition for increase the yield particularly in areas with low fertility status and it is also an effective way to decrease down the use of costly inorganic chemical fertilizers (Gil et al. 2018; Duncan et al. 2018). Where the efficiency is more the loss of nutrient is less. In China, the efficiency of mineral fertilizer is about 26–28% for cereals such as rice, wheat, and maize.

Nitrogen (N) loss from agricultural field is more than the other mineral fertilizers. Depending on soil type and amount of rainfall about 15–40 kg N ha^{-1} leach down

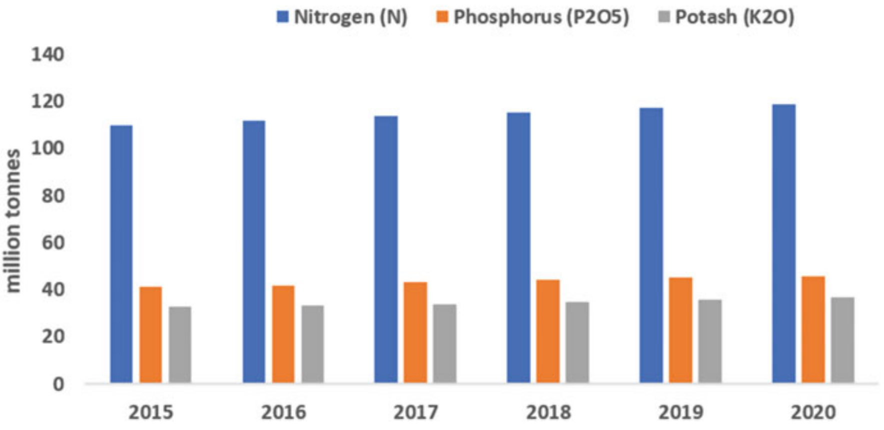

Fig. 18.3 Global demand for fertilizer nutrient use (FAO 2017)

from soil and pollute the groundwater. About 50–75% of the applied N is used by the plant in intensive agricultural system and rest is lost through various processes such as leaching, denitrification, surface run-off, volatilization, and microbial assimilation and most of these pollute the surrounding environment and decrease the air and water quality. Increase in 1% nitrogen use efficiency could save USD 1.1 billion annually as the N-fertilizer is expensive. The global N use efficiency for cereal crops was estimated to be 33% (Raun and Johnson 1999).

Applied fertilizer phosphorus (P) also lost from the agricultural fields through different processes of soil erosion due to water. However, the loss is smaller than the nitrogen. Only 15–30% of soil applied P fertilizers are taken up by the plants in the year of P fertilizer application to soil (Syers et al. 2008). However, the figure is 15–20% in China (Zhang et al. 2008). In India P utilization by crop plant is in the range of 15–30% (Tiwari 2001). According to Fertilizer Association of India consumption of P_2O_5 in India increased from 0.009 million tons in 1950–51 to 6.91 million tons in 2018–19. The global P fertilizer consumption of 4.78 million tons in 1961 increased by 3.5-fold to 16.67 million tons in 2013 while the phosphorus use efficiency for cereal crops was estimated to be only 16% (Dhillon et al. 2017).

Potassium (K) deficiency is most common in the soil around the earth. Only 1–2% of total K remain soil solution as the plant available K (Sardans and Peñuelas 2015; Dhillon et al. 2019). About 72% of agricultural soils in India require immediate and frequent K fertilization for improved crop production (Yadav et al. 2020). In China, 25% arable soil and 75% of paddy soil are deficient in potassium (Römheld and Kirkby 2010). K use efficiency in global cereal crops found only 19% (Dhillon et al. 2019). The potash (as K_2O) supply in world in 2013 was 44.18 million tons in 2016 which is expected to grow to 52.75 million tons and 54.2 million tons at the end of 2020 and 2022, respectively.

18.3.6 Pesticides

About two million tons pesticides were used in different countries of the world in 2013–2014 out of which 17.5% are fungicides, 29.5% are insecticides, 47.5% are herbicides, and 5.5% are other pesticides (De et al. 2014) and it is estimated that the global pesticide consumption may increase to 33.5 million tons by end of 2020 (Zhang 2018). China, USA, Argentina, Thailand, Brazil, Italy, France, Canada, Japan and India rank in top ten positions in the world for maximum pesticides consumption (Worldatlas 2018). Directorate of Plant Protection, Quarantine & Storage, Ministry of Agriculture and Farmers Welfare of Government of India estimated that 56,268 tons of pesticide were used in different states of India in 2014–2015 and it increased to 56,720, 58,634, 63,406, 59,670 and 60,599 tons in 2015–16, 2016–17, 2017–18, and 2019–20, respectively. Pesticide use per hectare of cropland is increasing since 1990 (Fig. 18.4). The maximum rise in the pesticide use is observed in Israel and China than other countries and territories. In China it increased almost 2.23-fold from 5.87 kg ha^{-1} in 1990 to 13.07 kg ha^{-1}in 2017. However, in African countries and in India the pesticide uses per hectare did not much change during this period (FAOSTAT 2019).

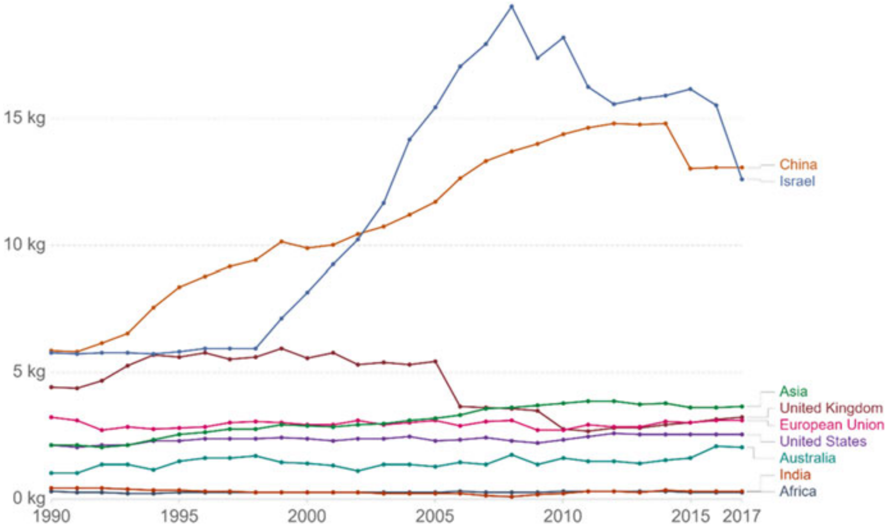

Fig. 18.4 Pesticide use per hectare of cropland in different countries and territories during 1990–2017 (Source: FAOSTAT; https://ourworldindata.org/pesticides)

18.4 Plan and Policy for Food Security (National and International)

It is a dream of every country that there will be a drive towards making a food- and nutrition-secured nation. It is because of the eradication of the "hunger and malnutrition" which are not desirable by the world that has both the knowledge and the resources. On assessment of the severity of the global food and nutritional status, Food and Agriculture Organization (FAO) and the World Health Organization (WHO) convened the first global conference to address the world's nutrition problems, in the International Conference on Nutrition (ICN) at FAO Headquarters in Rome in December, 1992. It is really important to assess the elements for understanding food security and nutrition policy in general which will focus on ensuring the sustainable food production, processing, distribution, and consumption and also to realize the optimal food quality and safety. It requires the combined efforts for sustainable nutrition and food security for monitoring the nutrition for a healthy lifestyle of the community. In order to streamline the process in setting out the policies on global food security and nutrition, it requires to find out key stakeholders which may include, government, international, non-governmental organizations, industrialists, academicians, consumers, in framing food and nutrition policy. In doing so, role and importance of price signaling and credit policy in agriculture need to be addressed in place, so as to create a favorable environment for attainment of production targets (Thomas et al. 2013).

The stakeholders will have the understanding to assess the needs of the policy and will review the existing policy (*if any*) and identify the flaws in it. The users will themselves review the current nutrition and food status of the population to develop appropriate food and nutrition policy for developing action plans. Hence, an effective and strong monitoring and evaluation mechanism will be required to facilitate a nutrition surveillance system appraisal and follow up action. Besides, there are some important issues which will also be addressed to bring into the area of nutrition directly or indirectly. There may be a task of identifying and action planning on socio-economic development, agriculture, national nutrition, food - hygiene regulation and on food-labelling. Hence, there should be emphasis on researchable issues on health of the common people.

The major target for a nation is to ensure the food security to reduce poverty and malnutrition for which the key measures that could be adopted are:

1. Ascertaining a steady economic growth through promotion of small-scale business development, economic integration and economic diversification, import–export facilities of commodity.
2. Emphasizing human resources development through professional trainings and reforming existing educational systems.
3. Reducing the extent of poverty by rural enterprise development and urban renewal systems, where small and micro enterprise development schemes may be an important tool for these policies. This will also strengthen the involvement of the rural and urban unemployed youth for stabilising their livelihood.

4. There should be close association of the government/NGOs to promote better governance and empowerment in the community development programme (CDP).

18.5 Food and Nutritional Security

Any discussion through the seminars or conferences on nutrition may serve as an index of plan of actions for setting up of any positive planning. In 1996, the World Food Summit (WFS) reinforced the validity of the goals and strategies identified at the International Conference on nutrition (ICN) in 1992. Based on that, an emphasis was envisaged to fulfil the pledge to accomplish food and nutritional security for all at national, regional and global levels to obtain a meaningful result. The twists and turns of the evolving story of world food security (Shaw 2007) was observed so closely that gave an impact the need for developing a comprehensive framework for the world food security. In doing so, the policy makers have to face challenges on the issues like natural calamities, growing infectious diseases, global market economy on available food materials, etc. To ensure the effective implementation of food and nutrition programmes at local or national level, much deliberation was given by the planners to bring it into an action plan. Some of the issues should still to be flagged on demand and supply for availability and consumption of food materials as well as on safety, hygiene, and nutrition. The major factors which need to be addressed to fulfil the action plan in national food security are:

18.5.1 Existing Trend in Food and Nutrition

It has been observed that, there has been a change in the last few decades on global nutritional scenario which might have its possible negative and positive impacts on the overall food and nutritional issues. There is increase in food production, increase in the improved variety of foods for globalizationand technology adoption, increased awareness on food safety and preservation technology, greater awareness on nutrition among the community. Although, there is some negative changes on market-driven food economy. The traditional foods are being replaced with more refined which are less healthy. There is increase in consumption of junk/fast foods, causing obesity and diabetes, hypertension, cardiovascular disease (CVD), cancer as well as infectious diseases. The deficiency of iodine (Szybiński et al. 1993) in human health sometimes became the key factor while assessing the malnutrition in a country. Due to this uncontrolled open marketing systems, some of the countries are facing double burden of under-nutrition as well as over-nutrition.

18.5.2 Issues on Nutrition and Health

1. To revamp the food policy, the production to marketing of food materials are to be considered in the first phase.
2. Encouraging and implementing self-sufficient economy in a country. Unhealthy food products should be identified and banned.
3. Harnessing the area-specific multi-sectoral and multi-pronged approaches on food and nutritional policy and plans of action keeping in mind the impact of environmental issues.
4. More emphasis is to be given on child health care by providing nutritional food or complementary feeding even during the environmental stress situation.

18.5.3 Constrains in Implementation

It has been observed that, even after rigorous planning and strategies there are barriers for successful implementation of a programme. The hindrances are felt and possible obstacles in their effective implementation are identified. Those are:

1. Limited trained technical personnel and support.
2. Lack of commitment and intersectoral coordination.
3. Low prioritization on food safety and nutrition.
4. Natural disasters and global climate change.
5. Knowledge gap between the stakeholders and policy makers.
6. Insufficiency in budgetary provisions.
7. Lack of trained manpower in the field of nutrition.
8. Globalisation and open trading system.
9. Uncontrolled and expensive price on commodities like fruits and vegetables.
10. Difficulty in understanding to approach the poverty groups.
11. Timelines in implementing, monitoring, and evaluation processes.

18.5.4 General Policy on Food and Nutritional Security

For translating policies and plans into action the followings are to be addressed:

1. More investment through the PPP (Public–Private Partnership) mode in agricultural production systems on the targeted small holders in rural sectors.
2. Encouraging involvement of youth in Agriculture.
3. Strengthening regional, national, and international relationships/ agreements and protocols to facilitate improvement in production and marketing resources.
4. To develop food safety and quality control protocol to impose among the food processors, food handlers, and consumers.
5. To provide basic health and nutritional support to undernourished or malnourished people.

6. To reduce micronutrient deficiency (e.g., iron deficiency related to anaemia) specifically for children, pregnant, and lactating women.
7. To establish legislation for the protection and upgradation of child nutrition.

18.5.5 Climate Change and Food Security

The National Action Plan on Climate Change (NAPCC) was formulated and launched in June, 2008 to ensure major focus on enhancing energy efficiency; increasing the penetration of solar photo-voltaic and solar thermal in the total energy, developing climate resilient sustainable habitats; integrated water resource management; a green mission for enhancing ecosystem services of forests and for increasing its carbon sequestration capacity; a mission on safeguarding Himalayan ecosystem and developing strategic knowledge on climate change. The renewable energy source (solar energy) may be an alternative tool for supplying energy to the domestic usages (Kapoor et al. 2014) which can cut short the cost of utilizing the non-renewable sources of energy on earth. To make such policies into implementation a territorial approach is necessary within India and prioritized action plan should be developed state wise to adopt National Action Plan on Climate Change. The prioritized location /region specific action plan on the basis of the changing climatic scenario will definitely have an impact on translating the food policy into the effective action and safeguarding the nutritional security of the stakeholders as well (Konda 2018).

Based on the Mid-Term Appraisal of Tenth Five Year Plan (2002–2007) in the 51st meeting of National Development Council (2005) of India, a platform was developed to flag the issues related to the minimum supply of year-round food grains to the nations. A resolution was adopted in the National Development Council (NDC) in its 53rd meeting held on May 29, 2007, to launch Food Security Mission comprising of rice, wheat, and pulses to raise the annual production of rice by ten million tons, wheat by eight million tons and pulses by two million tons by the end of the Eleventh Plan (2011–12). The Centrally Sponsored Scheme, “National Food Security Mission” (NFSM), was launched in October 2007. The mission achieved additional production of rice, wheat and pulses. The mission continued during 12th Five Year Plan with new targets of production of 25 million tons of food grains, by the end of 12th Five Year Plan.

18.6 Action Plan for the Environmental Security

It requires to pursue accelerated changes on social and economic development while comparing the food and nutritional security with the environmental one. The issue of development being an imperative for us for adaptation has to be more focused considering the global climate change and its impact on agriculture, health, sea-level rise, disaster, and also in national economy. The continuous impact of climate change is the world’s greatest challenge in the twenty-first century (Fry

2008). To reduce the emission of green house gas (GHGs) under the Integrated Energy Policy, 2006, there should be energy efficiency tools in all sectors and for which emphasis was given on mass transport, renewable including biofuels and fuel plantations, development of nuclear and hydropower technology missions for clean energy as well as focusing more on developing climate change related technologies. The National Solar Mission, Mission for Enhanced Energy Efficiency, Mission on Sustainable Habitat, Water Mission, Mission for Sustaining the Himalayan Ecosystem, Mission for a Green India, Mission for Sustainable Agriculture and Mission on Strategic Knowledge for Climate Change have been taken into cognizance. Periodic monitoring of these missions will help to derive the outcome for translating the strategic plans into action.

18.7 New Approaches for Adoption

With the changing pressure on population and global climatic scenario, the strategies to increase the potential zone of higher production of food are to be oriented to meet the requirement of food and other essential resources where agricultural production systems play the key role. Food production is strengthened with seed, water, labor, land, financial investment, and modern technology which could improve production potential in agricultural output. Some of the strength and weakness are there to address the situation for a better production outreach in a country.

18.7.1 Natural Resources

Land and soil are the major natural resources which are sometimes become degraded due to problems in water quality, soil erosion, soil salinity, and alkalinity and water stagnation in the field. The faulty and poor quality water supply for giving irrigation to the crops may cause problems in the food chain as a whole. Hence, to combat the situation, the land should be utilized according to its ability for improving the soil fertility and productivity, strengthening watershed management and monitoring the adverse of exploitative developments, especially with respect to pollution and ecological imbalances.

18.7.2 Water as a Key Factor

Water is a renewable resource which is essential for maintaining human health, support the health of aquatic ecosystems and for industrial development in maintaining water cycle as well as in many religious and cultural activities. Still there are some problems as this wonderful resource is under pressure and it requires review on causes of water scarcity and mechanisms for optimising water use efficiency (WUE) on priority. The water harvesting structures and effective water utilization pattern should be prioritised as a national water policy under the changing groundwater reserve in the country.

18.7.3 Technology in Agriculture

The modern and improved technology in the field of agriculture has brought about massive changes in the twenty-first century to transform Indian agriculture to commercial one. Some of the important components are:

18.7.3.1 Biotechnology

The need for employing biotechnology in agriculture at present is being dealt by different Ministries/ Departments (viz., Ministry of Agriculture, Ministry of Environment and Forests and Department of Biotechnology, Ministry of Science and Technology) to set up a comprehensive framework for augmenting quality production of the output. Different committees like the Recombinant DNA Advisory Committee (RDAC), the Review Committee on Genetic Manipulation (RCGM), the Institutional Biosafety Committee (IBSC), The Genetic Engineering Approval Committee (GEAC) have been formed to monitor the rules for manufacture, import/ export /storage /use of hazardous microorganism / biosafety of the Genetically modified (GM) crops, etc. The Task force under the Department of Agriculture and Cooperation, (2003) was set up to monitor the application of biotechnology in agriculture under the Chairmanship of Prof. M. S. Swaminathan.

18.7.3.2 Quality Seeds

The improved seed is the most determinant factor in agricultural production potential on which the efficiency of other agricultural inputs is dependent that could meet the demand in diverse agro-climatic situation under existing cropping pattern. However, the development of new and improved varieties is required for maximizing yield potential of crops.

18.7.3.3 Information and Communication Technology (ICT)

Information and Communication Technology (ICT) plays a pivotal role in agri-rural development (ARD) planning. A comprehensive ICT policy will facilitate educational courses, public–private partnership (PPP), providing access and connectivity with rural–urban interactions. The instant communication to the rural people will deliver information to solve the problems while facing trouble in agricultural production systems.

18.7.3.4 Conservation Technology for Natural Resource Management

Resource conservation technologies (RCT) are being practiced by farmers in the form of zero and reduced tillage. The RCTs have beneficial effects on rice-wheat systems by lowering the cost of production and has impact on environmental safety.

18.8 Sustainable Strategies for Food and Environmental Security

Despite of several measures and policy interventions at national and international level hunger and malnutrition persist in millions of peoples around the globe not only for growing demand but also for increase in foodprices as well as change in dietary preferences. Addressing the challenges of hunger, malnutrition, and food insecurity United Nation's agencies and civil society organizations set the global development goals in the middle of the last century to be achieved by 2015. However, due to slow and unequal progress in some parts of the world the leaders from 189 countries and heads of 23 international organizations agreed and set eight Millennium Development Goals (MDP) to combat poverty, hunger, disease, illiteracy, environmental degradation, and discrimination against women and were aimed to be achieved by 2015. This deadline was further extended to 2030 by UN General assembly (Maurice 2013).

Strategic options to eradicate malnutrition and ensure global food security needs to be carefully addressed because of dependence of agrarian sector on different factors such as status and use of natural resources as inputs, rapid growth in population, changing dietary choices, technological advancements, income distribution, supply chain management, agricultural market mechanism, social and financial conflicts, climate change, etc. (FAO 2018). The sustainable strategies for the efficient growth food and agricultural sectors without affecting the environment require upgradation of existing agricultural technologies, development of skills in farm practices, adoption of new innovation of farming, increasing the efficiency of inputs and lowering the wastage of food, etc., so that the goal of "growth to efficient growth" to be achieved. Several other strategic options to need to be considered as follows:

1. Ensuring the rights of farmers to the land in which he/she cultivates especially for the woman, tenant farmers, and landless labourers.
2. Reform in market and trade policies to ensure the availability and distribution of foods as well as agricultural inputs within and across the nations.
3. Strengthening the extension strategies to aware the farmers, traders, and consumers about the technological development and impact of environmental degradation.
4. The rapid growth of population should be checked to decrease the food demand and increase environmental protection.
5. Increasing literacy rate and providing proper education to all is an urgent need to increase the food production, environment protection, and proper implementation of plan and policies.
6. Providing greater support to the small and marginal farmers to increase the productivity by efficient utilization of available native technologies and resources.
7. Encouraging crop diversification to ensure the nutritional security and lower the green house gas emission.

8. Intensification of agriculture to increase the productivity of inputs used.
9. Ensuring proper collection, storage and distribution of foods to minimise the food waste.
10. Promoting and supporting climate resilient agricultural system.
11. Proper management of water resources to increase water conservation.
12. Dietary behavior and food preferences of people needs to be understood.
13. Funding and promoting agricultural research and education.

18.9 Weakness of Plans and Policies for Food and Environmental Security

Driven by agricultural plans and policy initiatives the food production is increased in different countries with lower level of input use and thus made the system more sustainable. However, certain improvements in policy measures and execution are need to be considered to strengthen the fight against hunger and malnutrition defeating some weakness.

1. Weakness to resolve the issue of ownership of land is a major barrier to food security in many developing countries. If the land tenure remains unclear or the state claim all legal right, the investments will favour the big farmers or large-scale production avoiding the small and marginal farmers and shall affect the overall improvement of food production.
2. Inability to ensure the gender equality is an important issue for the failure to eradicate hunger.
3. Weakness to ensure pure market mechanisms in agri-food sectors affects the flow of inputs in local small markets.
4. Input pricing policy and subsidies sometimes distort agri-production. For example, irrigation subsidy discourages the farmers to use water saving irrigation systems. Subsidies to fertilizers creates a barrier to use environment safe organics.
5. Weakness of policy intervention to reduce the problem of volatility in both agri-input and agri-product markets creates strong constraints and increases risk of unstable price.
6. Weakness to create mass awareness among the agri-producers about the benefits of using improved agri-technologies such as farm machinery, certified seeds, etc.
7. Weakness of policy incentives to acquaint the farmers about the application of inputs as per recommendation to increase input use efficiency and decrease of environmental degradation.
8. Agricultural policies and political governance must be strengthened to attract both public and private investments in agricultural sector.
9. Weakness still exists in participatory decision making involving the local people protecting their opinions, rights, culture, and interest.
10. Lack of commitment to fight against the global climate change.

18.10 Epilogue

The world is still hungry. About 8.9% of global population that is nearly 690 million people are hungry despite the increase in the food production driven by plan and policy incentives taken by the government of different countries as well as the international organizations after the green revolution. Prevalence of food insecurity and malnutrition are the greatest challenges to achieve "Zero Hunger" by 2030 set by the United Nations as the second goal of the sustainable development. Meeting food security remains always a challenge as demand of food is ever-increasing and it increases with the increase in global population. The current demand for food is expected to increase anywhere between 59–98% by 2050. It is the urgent need to provide food for these hungry people while at the same time it is also important to go beyond hunger and ensure easy access to the nutritious and preferable food in sufficient amount. Human wellness depends not only on the access to food, cloth, and shelter but also freedom to choose them as per their preferences. Besides that, the unhealthy diet is also an important factor which is also affected the human health. Obesity is increasing at an alarming rate especially in the urban affluent population. The global number of obese people surpassed the number of undernourished people already in 2016.

The present chapter has discussed about the plan and policy initiatives of different national and international levels to increase the input use efficiency and to provide sufficient nutritious foods to 100% people in sustainable manner and also protecting environment as well. But it is true that unless we achieve a quantum jump in the global food production and productivity the dream to feed 100% world population shall remain a dream. Such increase in current food production may be achieved by the efficient use and management of the available resources as inputs keeping aside the other climatic factors. The development of resilient and sustainable agricultural system with minimum exploitation of natural resources to provide healthy diverse diets as per need of the people is always an important issue for the policy makers. A number of national and international policy interventions have increased the food production around the globe and facilitated and encouraged the farmers to adopt better technologies to increase efficiency of input used so that the surrounding environment get less affected with residual effects of inputs.

However, while increasing food production nobody should forget about the environmental security. Agriculture was not environmental degrading agent for thousands of years until adoption of modern technologies, cultivation of heavy feeder high yielding varieties and indiscriminate use of agro-chemicals to increase the yield. Now, agriculture is not blamed rather truly a major cause of degradation of ecosystem; land, water, and air pollution. Development and proper implementation of further plan and policies in this regard is an urgent need to encourage the use of natural renewable resources in sustainable manner as agricultural input for increasing yield as well as protecting environment. The governments should further strengthen the monitoring mechanisms for the production, supply and use of inputs especially for the agro-chemical following national and international laws and guidelines.

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Precision Input Management for Minimizing and Recycling of Agricultural Waste

19

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Abstract

Agricultural production system, being one of the most important and dynamic sectors, significantly alleviate climate change, which directly or indirectly results in emissions of greenhouse gases (GHG's). Several strategies and technological interventions have been made that have resulted in reducing greenhouse gas emission, but it should not by any means reduce the farm revenue and productivity. Apart from this, the age-old traditional methods of cultivation have raised several concerns related to water drainage, fertilizer consumption, and waste disposal, etc. Optimizing agricultural waste and also enhancing food productivity simultaneously to feed the ever-increasing world population is an urgent need of

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the hour. In these aspects, smart agriculture which often incorporates technologies for improving farming operations, improving water management, fertilizer applications and finally crop production by means of sensor-based equipment's have proved to be fruitful. Under the agricultural production system, it is a well-known fact that a significant amount of wastage is created as trash and bagasse. These wastages present within the system itself can be a precious alternatives resource if suitable waste to loop mechanism is applied. For example, in cities and towns, several sensors-mounted trash-collecting vehicles are used to monitor total waste load and identifying the best alternative path for waste collection for efficient management. It is, however, a matter of fact that in most of the countries around the globe the smart agriculture has failed to integrate and incorporate waste management techniques altogether as a whole. Thus, the use of sensors, GPS, etc., can help in waste management by utilizing the loops through incorporation of cost-effective means of waste collection, transportation economic resource utilization techniques. Thus, under this context, the chapter aims to find the different alternatives and roles of effective waste to gold creation opportunities within a smart agricultural production system.

Keywords

Waste management · Smart agriculture · Precision agriculture · Resource utilization

Abbreviations

AWMS	Agricultural waste management system
DGPS	Differential global positioning system
FIS	Farm Information Systems
GDP	Gross domestic product
GHGs	Greenhouse Gases
GIS	Geographic Information System
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IoT	Internet-of-Things
IRSS	Indian Remote Sensing Satellites
LCA	Life Cycle Assessment
LORIS	Local Resources Information System
NUE	Nitrogen Use Efficiency
PA	Precision Agriculture
RFID	Radio-frequency identification
RS	Remote Sensing
SD	Standard Deviation
SEPA	Scottish Environmental Protection Agency

SPOT	*Satellite Pour I'Observation de la Terre* (French National Earth Observation Satellite)
SSA	Sub Saharan Africa
TM	Territorial Metabolism
USDA	United States Department of Agriculture
VRA	Variable rate application
VRI	Variable Rate Irrigation
VRNA	Variable-rate nutrient application
VRPA	Variable-rate pesticide application
VRT	Variable Rate Technique
VRTA	Variable Rate Tillage or Seeding Application

19.1 Introduction

Agricultural production and allied sectors is one of the most important sectors that directly influence global food security and safety. Simultaneously it also results in several environmental impacts resulting from water shortage, production of wasteful agricultural bagasse, emission of harmful greenhouse gases (GHG's), energy utilization and rampant use of fertilizers that cause ground water and soil health contaminations. Sustainable agriculture in this aspect has proved itself to be potential alternatives which focus on producing more and reducing and managing agricultural waste protecting the environment at the same time. As per Andrieu et al. (2017), climate-smart agriculture considers into account smart innovative solution techniques for enhancing agricultural productivity, improvement in climate resilience and reducing the emission of harmful GHG's. Similarly, Precision agriculture also supports need-based optimal usage of farm inputs at the right amount, right time following right application methods, maximizing the farm profit with minimalistic impact on the environment (Shirish and Bhalerao 2013; Kumar and Meena 2020). As per the report submitted by Scottish Environmental Protection Agency (SEPA) (2005), agricultural wastes are generated from the various point and non-point sources which include animal and human faeces, beddings, carcasses, dairy parlour washes, waste and rotten milk, feed runoffs, abattoir waste, animal viscera's, feathers, blood, fur, cereal husks, sheel kernels, etc. Apart from these agricultural wastes are generated from sugarcane bagasse, waste wood, plastic packaging bags, teared out machineries, waste food, tyres, etc. These waste generated results in a tremendous threat to the environment creating health hazards to farmworkers as well as livestock. Similarly, as per the report of United States Department of Agriculture (USDA) (2013), due to ever-increasing population of the farm women from 1982–2007 are prime target and threats of agricultural waste. Robin (2001) reported that a single hog and cow can produces almost three times waste and 20 times respectively as compared to human beings. According to the study of Nagendran (2011), India ranked top among the major contributors of agricultural wastes

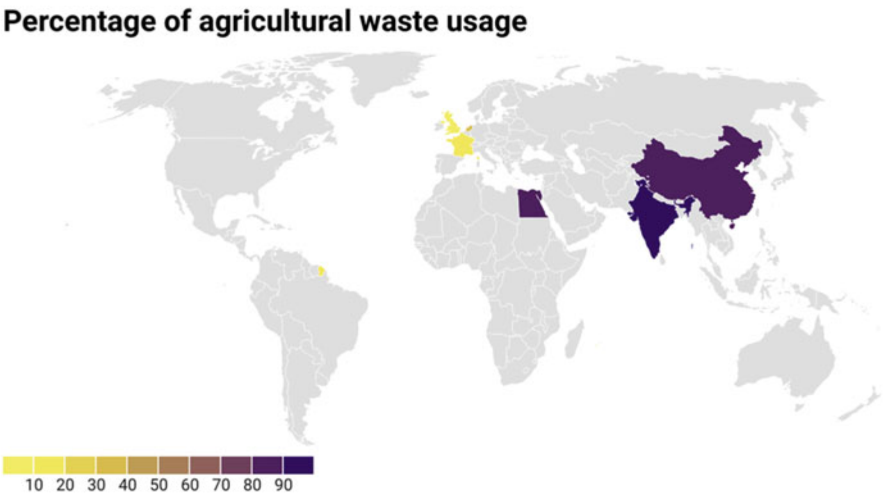

Fig. 19.1 Leading contributors in the agricultural waste generation (Data Source: Nagendran 2011)

followed by China, Egypt, Netherlands, France, and the United Kingdom (Fig. 19.1).

From the late 60s, industrialization, urbanization, increasing population density over the time frame has resulted in a drastic increase in waste accumulation. These waste materials comprise of several components such as radioactive substances, agricultural waste, food waste, municipal sewage waste, industrial waste products, etc. Intensive farming an over-increasing population has resulted in a substantial decrease in land for waste disposal. Alok et al. (2008) suggested that there should be an integrated approach for collection, transport, disposal, recycling of waste products to cut down the waste load. Agricultural waste management system (AWMS) has been briefly discussed in this chapter considering the concepts, techniques, and elaborative methodologies for judicious and economic waste (Kumar et al. 2018). Agricultural Waste products have varied range of direct and indirect harmful effects on the environment along with toxic effects on the living world. The chapter aims to find the different alternatives and roles of effective waste to gold creation opportunities within a smart agricultural production system.

19.1.1 Introduction to Agricultural Wastes

The waste/residues that are generated as byproducts of growing and processed agricultural products such as vegetables, cereal bagasse, fruits, poultry, meat byproducts, etc., can be termed as agricultural waste. These wastes are generally unproductive outputs of production and processing systems which often contains beneficial components for human sustainability having economic values lesser than required to process, collect or rather transport for using it in reality. Agricultural waste or agro-based waste products generally comprises of manual and animal remains food processing waste, various waste from crops such as sugarcane bagasse, cornstalks, fruit and vegetable drops, etc., and also toxic and harmful input plant protection waste materials such as insecticides, herbicides, and pesticides (Kumar et al. 2021). Though there is no clear cut indication of quantifiable agricultural waste yet, it is a consensus that it contributes significantly towards waste matter production globally. There is a significant for enhancement of agricultural waste production with an increase in global agricultural production especially by developing nation due to the intensification of the production system. Several studies have estimated that about 998 million tons of agricultural waste are created annually (Agamuthu 2009). As early as during the late-ninetieth century it was estimated that about 80 per cent of the total solid waste products comprises of organic products which are produced by agricultural farms (Brown and Root Environmental Consultancy Group 1997). Manures production itself amounts nearly 5.27 kg/ day/1000 kg live weight organic waste on a weight basis (Overcash 1973). Most of these wastes are released untreated into the environment without maintaining safety norms thereby causing toxicity harmful to living worlds. GHG emission from these wastes is a major concern for environmentalists. Thus, it has become a global concern for improvements and creating cleaner and greener renewable bioenergy gases (Okonko et al. 2009). Studies conducted shows that different wastes such as peels from lemon, pomegranate, husks from walnuts can be efficiently used as an alternative to antimicrobials (Adamez et al. 2012; Katalinic et al. 2010). Some of the agricultural residual waste can be used as animal food despite variations in nutritive values such as protein, sugars, and minerals (Graminha et al. 2008). Considering the nutritional aspects these residues are not “wastes” but considered as basic raw components or substrates for other materials. These raw products can be used for the growth of several beneficial microorganisms. The conversion of these residues is very important for economic betterment and well-being of the living beings, which indirectly reduces the pressure in the land, harmful effects on biodiversity and negatively impacting the global food safety and security (UNEP 2011).

19.1.2 Brief Accounts into Waste Management

Waste management as defined by Burke et al. (2005) is an integrated approach involving collection, disposal, transport, reprocessing, and close supervision of wastes. It is noteworthy to mention that waste management at times becomes costly; hence, it is of utmost necessity to understand the effective, safe and sustainable, judicious way out for of its efficient management policies (El-Haggar 2007). The principle of waste management lies in three R’s comprising of reducing, reuse, and recycle due to gradual increment in the deposition and production of wastes, processing-based cost and a slow and steady shrinkage in landfill spaces (Seadon 2006; Suttibak and Nitivattananon 2008; Tudor et al. 2011). Focus and emphasis must be given in waste management regarding flexibility under changing environmental, socioeconomic conditions (McDougall et al. 2008; Scharfe 2010; Meena et al. 2020). Regular feedback mechanism and analysis of system require optimization, evaluation, and adaptation (Pires et al. 2011).

In waste management, the top priority is given to the reduction of waste in the hierarchical system (USEPA 2010). Reuse of products may also be adapted as a great alternative for reducing waste. Reuse and reduction of waste not only saves natural resources but also diminish the underlying expenditures associated with the generated waste product disposal mechanism (USEPA 2010). As per a study conducted by Gajalakshmi and Abbasi (2003) waste management is a technological intervention to mitigate the ill impacts of wastes on our surroundings, health, and aesthetic values. Generated waste products may be in the form of solid, semi-solid, liquid, or gaseous in nature. The process associated with waste management technologies varies geographically, economically from urban to rural areas, industrial to municipal and from developed to developing countries around the globe. It is the responsibility of local authority for management of the municipal effluents whereas, the responsibilities lie over the generator in case of the industrial waste management and recycling (Verdone and De Filippis 2004). The developed European nations often incorporated various innovative and modern technological options to minimize the ill fates of the waste, harness, or exploit it to the fullest or manage it judiciously (Henry and Heinke 1989; Cunningham and Fadel 2007).

19.2 Category of Agricultural Waste

Agricultural wastes are defined as the residues from the growing and processing of raw agricultural products such as fruits, vegetables, meat, poultry, dairy products, and crops (Obi et al. 2016). They are usually considered as nonproduct outputs generated through various stages of production and processing of the agricultural system. Their commercial values are negligible compared to the cost involved in the collection, transport, and processing for any fruitful usage. The composition of agricultural waste or agro-waste is dependent on the cropping system and pattern. They are usually found in the form of solids, liquids, or slurries. Agro-waste can be of various categories like animal waste (animal carcasses, manure), waste generated during food processing (For example, 80% wastage occurs during the processing of maize), crop waste (sugarcane bagasse, corn stalks, culls, and drops during pruning of fruits and vegetables), toxic and hazardous waste (herbicides, insecticides, pesticides).

As per the United States Environmental Protection Agency (USEPA), agrarian waste is the side-effects created by the raising of creatures and the creation and collect of yields or trees. Animal waste, a huge part of the rural waste, incorporates squander (e.g., feed waste, sheet material and litter, and feedlot and enclosure overflow) from domesticated animals, dairy, and other animal-related rural and cultivating rehearses. Association for Economic Cooperation and Development characterizes “agrarian waste” as waste delivered because of different horticultural activities including compost and different squanders from ranches, poultry houses and slaughterhouses; collect waste; manure run-off from fields; pesticides that go into the water, air or soils; and salt and residue depleted from fields. With regards to this section, rural waste is characterized as waste as the yield buildups in the homestead, compost from domesticated animals tasks, including dairy and piggery profluent, and poultry litter.

Agriculture forms one of the major sources of economy in India, employing half of its population. Agriculture contributed to almost 7.9% of total GDP formation. With agriculture retaining the position of the major source of employment and sustenance, the cultivation of various types of crops also leads to the production of huge quantity of agricultural and organic wastes in the form of leaves, kitchen wastes, and residues of animal feed, unused chemicals, animal dung, and other unproductive outputs. India generates about 350 MT of agricultural wastes every year. Reutilization of these unused materials in various forms could replace toxic chemicals and can also be beneficial to the society at cheap cost and ample supply.

19.2.1 Waste Generation from Cultivation Activities

Use of pesticides is one of the major sources of agricultural waste. Farmers often abuse pesticides by throwing the packages or bottles into nearby fields or ponds. These can, in turn, lead to several fatalities like food poisoning and affect food hygiene. The long-lasting toxic chemicals have the potential to contaminate the farming areas. Improper storing or burying of pesticide packages, unused or stagnant pesticides may lead to osmosis of these chemicals into the environment and causing severe environmental problems.

Farmers often try to maximize crop production by excessive use of fertilizers. The absorption rate of various compounds (e.g., potassium, phosphorus, nitrogen, etc.) present in fertilizer depends on various factors like methods of fertilization, land characteristics, types of plant. The excess fertilizers are not only retained in the soil but also propagate to various water systems like ponds, lakes, rivers, etc., by means of surface-runoff or through various modes of irrigation system. Thus, surface water is polluted through excess fertilizer. A portion of fertilizer also enters ground-water level and creates contamination. Evaporation or de-nitrification of fertilizers also causes severe pollution of the surrounding atmosphere.

19.2.2 Generation of Waste Products from Livestock Production

Wastes from different livestock production are mainly solid wastes such as manure of organic materials in the slaughter-houses, or liquid wastes such as—urination of animals, filthy water residue from their bathing, or washing of their living places, unused food remains, and other organic wastes. They emanate odour, pollutants such as H_2S, and also emits greenhouse gases from untreated waste material. The respiration of the animals in some cases also produces greenhouse gases which are becoming a matter of concern nowadays where industrial activities have already proposed a great threat to the environment. In animals squander, water volume represents 75–95% of complete volume, while the rest incorporates natural matter, inorganic matter, and numerous types of microorganisms and parasite eggs (Hai and Tuyet 2010). Those germs and substances can spread infections to people and cause many adverse impacts on the environment and climate.

19.2.3 Agricultural Residual Products

Many crops leave behind residuals after getting used. This includes molasses, pressmud, groundnut shells, bagasse, husks, paddy, wooden mills, and other plant parts that are organic and unusable. However, these types of wastes can be reutilized and are often useful economically. Bagasse can be used in ploughing the soil and for fertilization purposes, groundnut shells could be used as oilcake, pressmud could be used in the manufacture of shoe polish, and the organic remains are often used to increase the fertilizing capacity of the soil. These organic residues can be categorised under the reusable type of wastes that are helpful in one way or the other.

19.2.4 Waste from Aquaculture

Usage of feeds is increasing to maximize the production in the aquaculture sector. Ambient temperature controls the feeding rate. Higher temperature leads to increased feeding, which in turn generates a higher amount of waste. Most of wastes generated through aquaculture farms are metabolic in nature; therefore, can be suspended or dissolved easily. However, about 30% of the feeds turn into solid waste in a well-managed farm. Patterns of water flow in production units play a significant role in solid waste management. The fragmentation of fish faeces is minimized by proper water flow, which leads to rapid settling of the solids as well as the concentration of the settling solids. This is crucial for capturing large numbers of non-fragmented faeces, which in turn helps to reduce the dissolved organic waste (Mathieu and Timmons 1995).

19.2.5 Hazardous/Special Agricultural Waste

Special waste is a waste which has hazardous properties and is subject to additional controls to protect the environment and human health. There are several examples of special waste like waste pesticides and chemicals; asbestos roofing material, infectious waste arising from animal healthcare; waste oils from farm machinery; and electrical equipment containing cathode ray tubes.

19.3 Consequence of Agricultural Waste on Food and Environmental Security

Agricultural waste can impact the environment in several ways. Burning of agricultural waste is a common disposal practice for various under-developed as well as developing countries. This is responsible for air pollution as pollutants such as carbon monoxide, nitrous oxide, nitrogen dioxide, and particles like smoke carbon emit during burning (Ezcurra et al. 2001; Yadav et al. 2020). Additionally, ozone and nitric acid are formed as a result of waste burning which contributes to acid decomposition (Hegg et al. 1987; Lacaux et al. 1992). This, in turn, leads to severe risk to human and ecological health (Sabiiti 2011).

Different creature squanders are additionally a significant wellspring of natural contamination. Nations with high centralizations of creatures on a restricted land base for excrement removal may confront more genuine effects from this kind of contamination (Sabiiti 2011). Excretion of animal waste can have solid, liquid as well as gaseous form. Strong and fluid discharges (dung, pee, etc.) are changed over into microbial biomass and solvent and vaporous items essentially through an anaerobic interaction. Gaseous excretions are formed through respiration and fermentation also get mixed in the air. Some of these products contribute to air pollution, soil deterioration, and water quality degradation.

19.3.1 Consequences of Animal Waste Product

Application of excessive animal wastes on land as fertilizer and soil conditioner is subject to surface run-off and leaching that may contaminate ground or water (Sabiiti 2011). Nitrate leaching from animal manure is a major concern for livestock farms (Mackie et al. 1998). Phosphorus entering the surface waters through the use of manure can trigger the growth of algae and other aquatic plants. Their subsequent decomposition can increase oxygen demand of the water harming the fishes. Manure decomposition also contributes to GHGs through producing methane, ammonia, and nitrogen oxides. Acid deposition through volatilization of ammonia is a major contributor to acid precipitation (Lowe 1995; Likens et al. 1996). Emissions of nitrous oxide during the nitrification-denitrification cycle may cause ozone depletion (Schulte 1997).

19.3.2 Consequences of Ecosystem on Food Waste Generation

The total land used for the production of unconsumed food over the globe is roughly equal to the total cropland in the continent of Africa. This can be reduced significantly (almost by volume of Southeast Asia) by adopting best practices. Almost 25% of fertilizers are used to produce lost and wasted food in the United States. Also, a dead zone has been created in the Gulf of Mexico by farm runoffs in the United States. The size of this dead zone will be equal to the combined size of Rhode Island

and Connecticut. Almost 34 million metric tons of food get wasted in the US alone which is one-seventh of landfill mass. The methane emitted by this amount of food waste is equally dangerous to the emission generated by four million cars. The food loss and wastage on the global scale is equivalent to the combined impact of about 650 million cars. The consumer-generated waste which created at the end stage of value chain has the highest carbon impacts as it includes all the resources used in previous steps of food production and supply. Carbon footprint (per capita) of wastage is significantly greater in developed countries compared to sub-Saharan Africa.

19.3.3 Agricultural Wastes and its Consequences

According to Lin et al. (2009), agricultural wastes have a direct or indirect impact on food security and systems, especially for poor and vulnerable people (Fig. 19.2). The saleable volumes of crops are decreased by more than 15% by wastage due to the harvest period affecting families of 470 million smallholder farmers and 290 million people working downstream in the agriculture industry (DIC 2013). Farmers' inability to food storage leads to wastage, creating problems for them in coping with agricultural price fluctuation. Prices are more volatile in developing countries, causing more pressure on vulnerable peoples. More than 50% of food and vegetables and about 25% of cereals are wasted in developing countries of Asia, Africa, and Latin America. Thus, food availability decreases for 1.2 billion people facing inadequacy of food. As per studies on spending, consumers spend most of their incremental income (40–50%) on food in low-income countries. Higher food prices

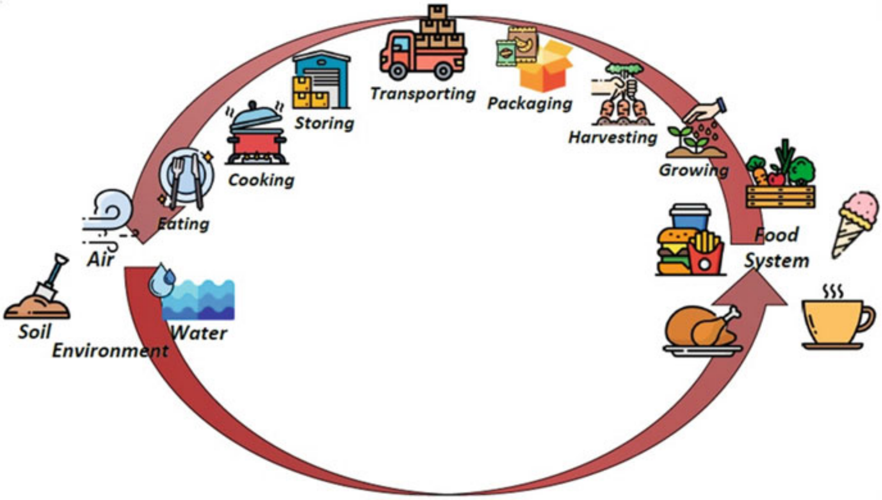

Fig. 19.2 Effect of agricultural waste on the environment on food system. (Prepared by Debjyoti Majumder)

due to wastage force consumers to spend more on food, which creates more poverty. To bring more people out of poverty, a sustained increase in food supply is more effective over the long term than the increase in farmers' income. Wastage of vegetables, tubers, roots, and fruits affects the dietary requirements needed for people's good health. Crops' nutritional value can be degraded due to improper storage, which can, in turn, affect consumers' health.

19.3.4 Role of Rampant Application of Fertilizer Input

Many countries are facing nutrient surpluses due to the over-application of fertilizers promoted by the wide availability and high cost-effectiveness of fertilizers. This leads to nutrient accumulation and environmental pollution in the developed countries, whereas exports of nutrients are causing rapid depletion of reserves in developing countries. The nitrogen balance deficit in sub-Saharan Africa has increased from 22 kg ha^{-1} in 1983 to 26 kg ha^{-1}in 2000 (Goulding et al. 2008). This accelerates the existing food security issues of this region, where it is very difficult to grow calorie-rich foods for local people.

19.3.5 Food Waste and its Role in the Environment

Excess food waste has several impacts on the environment. Waste is generated throughout the food chain from growing, harvesting, packaging, transporting, storing, and cooking, as shown in Fig. 19.2. The agriculture sector is one of the significant contributors to global waste generation. Seven billion livestock in the USA produces waste amounting to 130 times greater than its entire population (Marlow et al. 2009). Untreated waste may pose a greater threat to food safety and public health problems. The leftovers from farming like chemical fertilizers, pesticides, herbicides, and antibiotics contaminate the environment and affect our food.

19.3.6 Future Prospects of Agricultural Waste

Instead of negative impacts, it is possible to agricultural wastes make a useful resource. They can be utilized as bio-fertilizer, animal feed, soil amendment, and producing energy, which can enhance food security (Sabiiti 2011). Waste treatment technologies like transforming crop residues and animal manure into organic waste through the composting method can be beneficial for populated areas. Environmental problems regarding the disposal of large quantities of waste can be solved through composting as it helps to minimize the volume of the waste. Composting has several other advantages like the killing of pathogens inside waste, reducing odour, and decreasing the germination of weeds in the farmlands (Jakobsen 1995).

Crop residues and animal waste are equally useful as animal feed. However, animal waste's nutrient content depends on the type of feed, species of animal, and the material used for bedding (Mackie et al. 1998). Broiler litter is widely utilized in cattle feeding. Ruminant creatures can change over yield deposits into food, accordingly help to decrease possible poisons. The rumen comprises of microbial catalyst cellulose, which can process the most plentiful plant item, cellulose (CAST 1975). With ruminants, supplements in results are used and do not turn into a garbage removal issue (Oltjen and Beckett 1996). Agricultural waste has been used for energy production on various scales worldwide (Westermann and Bicudo 2005). Mackie et al. (1998) have suggested that waste-to-energy schemes have two benefits—firstly, generating revenue from energy and, secondly, giving another option and naturally adequate methods for garbage removal. It can also be useful for producing a good quality nearly odourless fertilizer.

19.4 Recycling Mechanism of Agricultural Waste

The out-of-place waste products comprising of crop residues, excreta, and faecal matters from poultry and livestock, toxic residual products from pesticides and fertilizers which are often produced from agricultural practices has been defined as agricultural waste (Wang et al. 2016) and hence indiscriminate use and unscientific dispositions of these products have not only resulted in environmental pollutions but has also lead to wastage of a lot of precious and nonrecyclable natural resources. With advancements in technological interventions in agriculture and allied sectors have significantly boosted up concentrations and accumulation of wastages beyond environmental safe limits which directly influences the environmental safety and natural balances. As per Wang et al. (2016) the annual growth rate of agricultural waste products are increasing at 5–10 per cent.

A burning and blazing issue under present-day conditions has been drastic and rampant burning of crop stubble and residues which not only have created havoc pollution to the environment in local scale but also in broader regional scales. As per a report by Kumar et al. (2014), the rampant burning of stubbles has caused 59,000, 20,000, and 34,000 tons of nitrogen, phosphorous, and potassium losses along with 3.85 million tons of soil organic carbon yearly. The adverse effect of residue burning results in the emission of harmful and toxic gases like methane, NO, $NH_{4,}$ SO_X particulates causing atmospheric pollutions and harmful impact on human health which often increases the problems related with asthma, bronchitis, lung cancer, etc. These emitted toxic gases often lead to or act as a nonpoint source of ozone pollution.

A present-day important issue in agricultural sector comprises of uncontrolled, rampant, non-judicious use of pesticides and fertilizer, disposal of containers and packing materials which directly results in soil, water, and air pollution (Wang et al. 2016). Consequently, these unscientific and non-judicious agricultural waste product management adversely affects human and animal health aggravating several critical diseases like arsenicosis (caused due to the drinking of arsenic-contaminated water),

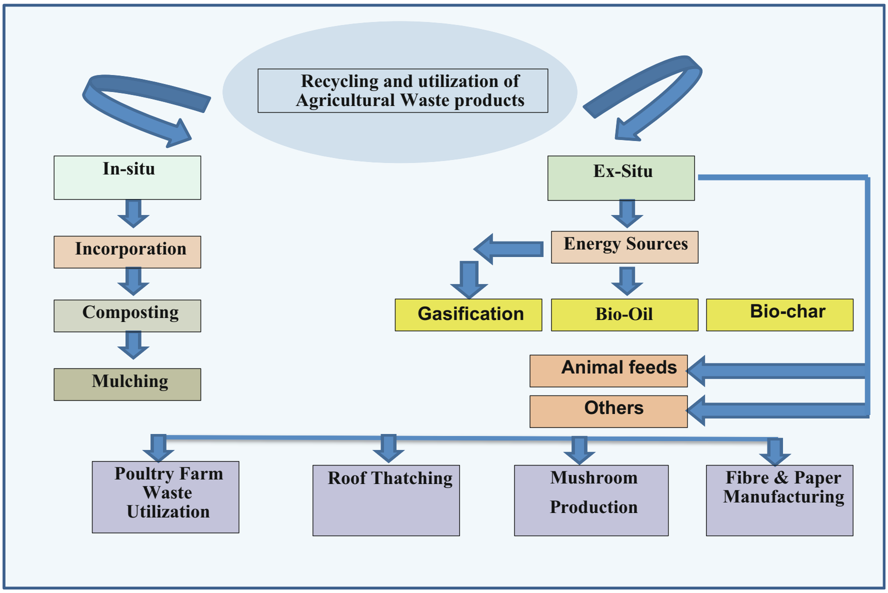

Fig. 19.3 Different mechanisms of recycling and utilization of agricultural wastes (Prepared by Debjyoti Majumder)

Blue baby syndrome (Due to high concentration of Nitrates in drinking water), lead toxicity, Etai-Etai (Mercury contaminations), etc., which are caused mainly due to contaminations ground water and surface water bodies by heavy metals due to seepage and leaching losses. When these toxic materials are directly disposed-off into water bodies viz., ponds, lakes, river bodies, etc., it often leads to contaminations of the aquatic and lacustrine environment thereby causing the death of marine and aquatic lives due to eutrophication.

Energy conservation and development of agriculture and allied sectors alongside maintaining environmental safety and protection can only be achieved through adopting scientific wastes recycling mechanism and utilization of waste. These can be achieved by adapting to management methodologies comprising of in situ and ex situ management (Fig. 19.3).

19.4.1 In Situ Management of Agricultural Waste

In situ method of management the system implies the reusing mechanisms of various agri-horticultural squanders created in the field or instead of their creation as it were. This could be possible in the following several methodological and scientific techniques as follows:

19.4.1.1 Incorporation of Crop Residue in Soil

Incorporating crop residual products in situ in soils always have a favourable impact on soil physical, chemical, and biological health and properties (Prasad and Power 1991) including, maintenance of soil pH, organic carbon retention within soil masses, enhancing water retention capacity, nutrient holding capacity, improving soil bulk density, soil temperature regulations. Alternatively, on long-term basis, it also helps in increasing the availability of soil nitrogen, phosphorous and potassium, zinc, manganese, etc.

Crop Residues retention and management also help in retaining soil nutrients mainly nitrates compound thereby preventing leaching losses. It has also been found to increase soil microbial flora and fauna to considerable level as a result of increasing soil organic content due to strategic residual management. Furthermore, the enhancement in enzymatic activities and better microbial activity within the soil profile helps in transformation of nutrients from unavailable form to available forms (Kumar and Goh 2000).

19.4.1.2 Mulching

Using crop residue as a mulching material help in retaining soil moisture, optimization of soil temperature, weed population check which in the forerun helps in gaining increased productivity and better return (IARI 2012). Mirsky et al. (2013) concluded that mulching has substantially proved to be beneficial in terms of irrigation saving and also suppressing the weed growths throughout the crop growing period of the standing crop.

19.4.1.3 Compost Making

Preparation of composts by utilizing crop residues, weed plants, and other vegetative parts (Edwards and Araya 2011) like *Eichhornia crassipes, Parthenium hysterophorus,* etc., and other rogues not only helps in enhancing the soil fertility and soil microbial populations (soil flora and fauna) by decreasing indiscriminate use of chemical fertilizers but also helps in controlling and checking the environmental pollutions to a considerable extent due to its sufficient nutrient contents (Table 19.1). The technologies have substantially proved to be fruitful in reducing the cost of productions and thereby enhancing the profitability margins of the farmers.

Preparation of *Parthenium* Compost

- A pit size of dimensions 3 ft. depth, 6 ft. width, and 10 ft. in length need to construct under open and shady upland conditions.

Table 19.1 NPK Content in *Parthenium* and Field Side Compost (Data Source: Ghosh et al. 2018)

Name of the compost	Nitrogen (%)	Phosphorus (%)	Potash (%)
Parthenium compost	1.21	0.89	1.34
Field side compost	0.64	0.86	0.75
Farm yard manure	0.45	0.30	0.54
Vermicompost	1.61	0.68	1.31

- The entire pits including the base and the four-side walls need to compact either with stone chips or soil surface sealants like lime to prevent leaching loss of produced compost to the surrounding soil strata.
- The first layer of the pit should be filled up with 40 kg of soil should be used at the base of the pit.
- The second layer of the pit should be filled up with 30 kg of dry decomposed FYM / Vermicompost.
- The third layer should be filled up with non-flowering young parthenium plants from the nearby surrounding field and areas and evenly spread at 50 kg over the second layer comprising of FYM/ Vermicompost.
- The fourth part of the first layer should be spread with 500 grams of Urea or 3 kg of Rock phosphate evenly over the parthenium plants.
- 10 litres of freshwater should be sprinkled over which comprises of the fifth part of the first layer.
- The final sixth part of the first layer should be sprinkled with 50 grams of Trichoderma viridaeor similar kind off biofertilizers.
- The same procedure should be followed and repeated three more times thereby comprising altogether four layers.
- Finally, the pit should be covered with soil, fresh cow dung and husk making 1–1.5 ft. dome-shaped structure.
- After4–5 months, the well-decomposed compost will be ready which needs to be sieved before applications into the field.
- Packaging it in bags and using it later may also be done by the farmers after sieving the final products having a mesh size of 2 cmx 2 cm.

The low-cost ecofriendly balanced *Parthenium* compost can be used in cereal crops, vegetables, or in the perennial orchard at the rate of 3–5 5 t ha^{-1}. These compost are cheap as compared to traditional FYM, Compost or even vermicompost without any harmful effects.

Procedure of Making Other Field-Side Compost

- A compact pit of 2 ft. depth x 4 ft. width x 6–8 ft. length is to be dug out using lime in all walls.
- 20 kg soil is to be used at the base of the pit (first part of first layer)
- 20 kg dry decomposed FYM/vermicompost is to be added on the soil (second part of first layer)
- The uprooted weed plants and crop residues collected from the field or nearby areas are to be spread at the rate of 50 kg, evenly on the dry decomposed FYM / vermicompost (third part of first layer).
- 100 g Urea or 1 kg Rock phosphate needs to be sprinkled over it (fourth part of first layer)
- 10 lit of freshwater is to be sprayed on it (fifth part of first layer)
- Trichoderma viride or similar bio-fertilizer at the rate of 50 g needs to be sprinkled over the layer (Sixth and final part of first layer).

- All the six parts are to be repeated for similar three more times to make a total of four layers.
- The pit is to be covered with soil, dung and husk making a 1–1.5 ft. dome shape.
- After 4–5 months the well-decomposed compost will be ready to use.
- Sieving of the final compost with 2 cm × 2 cm mesh will make it ready to be applied at the rate of 3–5 t ha−1.

Presently the *Parth-Pana* Compost can be made by using alternate layers of *Parthenium hysterophorus* & *Eichhornia crassipes* in the above-described procedure.

Improved Technologies for Vermicompost Production

- The composting unit needs a cool, moist, and shady place for getting prepared.
- Chopped Crop residues are mixed with cow dung in 1:3 proportion and are left for 15–20 days for partial decomposition.
- A 15–20 cm of partially decomposed layer of chopped dried leaves or grasses, i.e., crop or weed residues are used as bedding material at the bottom of the bed and the pit or trench area are generally maintained at a size of 6x2x2 ft.
- Generally, each bed contains 1.5–2.0q of raw material and as per the raw material availability and requirement, the number of beds can be decided or increased.
- Red earthworms viz*.,* *Eisenia foetida* of about 1500–2000are to be released on the upper layer of the bed.
- The immediate sprinkling of water is needed after release of the worms.
- The beds needs to be kept properly moist by sprinkling water on daily basis and there by keeping them covered with gunny bags, etc.
- For maintaining proper aeration and proper decomposition, the bed needs to be turned once after 30 days.
- The vermicompost gets ready for application by 45–50 days.
- The final compost becomes almost three-fourth of the raw materials used.

Improved Production Technology for Farm Yard Manure (FYM)

FYM is one of the most traditional and potential manure often used and prepared by the farmers as a source of organic manure, which have proved to be a good alternative in terms of agricultural waste recycling mechanism. FYM is one of the most easily available manures which is produced out of well-decomposed cattle dung and urinal mixture soaked crop straws, husk, or other crop residual matters.

The unused, waste products from livestock sheds comprising of dung and urine soaked straws are collected at regular interval and are being placed in dugout trenches having dimensions of 6–7 m length, 1.5–2.0 m width and about 1 m in depth. These trenches are covered with soil and cowdung slurry upto 0.5 m above ground level resembling dome-shaped appearances. Almost after 3–4 months, the product is ready after complete decomposition for application in the crop field. This method of compost preparation can be used for producing nearly about 5–6 tons/ 10–12 tractor carts or about 7–8.5 cubic metre of final compost per year.

19.4.2 Ex Situ Management of Agricultural Waste

Lohan et al. (2018) defined ex situ management as recycling of agricultural wastes which are produced away from the field or site of origin. The process involves shifting of crop and animal residues away from the site of production to nearby locations where recycling of the materials are to carried out.

19.4.2.1 Utilization of Agricultural Wastes as an Alternative Source of Energy

Crop residues can often be utilized as a source of fuel in different biogas plants for the generation of power or electricity (IARI 2012). The analytical studies of the lifecycle of *Jatropha gossypifolia /curcas*plant under Euphorbiaceae family have potentiality and capability of producing favourable energy balance for *Jatropha* based biodiesel in India. It has also shown promising result in reducing GHG emission by almost 33–42% as compared to fossil fuel-based diesel. In the year 2009, December Union government of India launched the National Biodiesel Mission (NBM) identifying *Jatropha*as the most promising bio-oil-borne plant. During late 2018, the honourable Supreme court of India issued a circular that allowed the sale of biodiesels by the retailers for the maiden time. Analytical test conducted by EPA have showed that the hydrocarbon emission by *Jatropha* plant is nearly half as compared to fossil-based fuel thereby reducing the carbon footprint. The extracted seeds from the Jatropha plants are crushed for extraction of biodiesel oil. The extracted oil after undergoing processing can produce a high-quality biodiesel that can be used in motor vehicles. The residual matter viz. presscake are further processed and utilized as biomass feedstock for power generation in electric plants and also used as an alternative source of fertilizer enriched in nitrogen. The oil cake from *Jatropha curcas* isprotein is enriched and can be used as the replacement of fish or livestock feed after detoxification. Nevertheless, alternatively, biodiesel can also be produced from oil extracted from a wide range of plants comprising of palms, soybean, rapeseed/ mustard, and even sunflower or safflower too.

Several research institutions and departments are now encouraging the production of electricity from bioprocessing of crop residues. Jalkheri, a village in Fatehgarh Sahib have drawn attention by setting up a 10 MW power plant as early as 1992 utilizing paddy straw as a source of fuel production and became fully functional since 2001 with a lease-cum-power purchase agreement between PSEB and the Jalkheri Power private Limited (Kumar et al. 2014).

Adoption of these technological interventions for recycling of wastes has not only helped to reduce over-utilization of fossil fuels but also have helped to check the emission of harmful GHG's emission to a considerable amount.

The process of bio-methanation which is another form of recycling process utilizes crop residues in a nondestructive way, to extract high-qualitative fuel gas and helps in manure production through recycling within the soils. Plant biomasses comprising of paddy straw mulches which are often converted into biogas consists of carbon dioxide (CO_2) and methane (CH_4). These final byproducts can also be used as fuels in multiple sectors. One tonne of paddy straw can produce nearly 300 cubic metres of biogas with 55–60% of methane content (IARI 2012). Another byproduct such as slurry has widely been used as manures in agricultural crop productions which is evident from several Research studies through technological demonstrations.

19.4.2.2 Gasification

This is a thermochemical interaction, in which fractional ignition of yield deposits (crop yield components) prompts the development of gas, which in further is used for power age after its decontamination. Gasifiers of more than 1 MW limit have just been introduced in certain states for "maker gas" age which is taken care of into the motors coupling with alternators for power age. 300 kWh of power can be created from one ton of biomass can (IARI 2012). This innovation can effectively be utilized for crop build-up use as pellets and briquettes.

19.4.2.3 Biochar Production

A high-carbon material called biochar is created through sluggish pyrolysis of biomass. Biochar is fine-grained charcoal, equipped for assuming a fundamental part in the drawn-out capacity of carbon in soil by GHG moderation and C sequestration (IARI 2012). The current degree of innovation needs greater improvement for its monetarily suitable creation and advancement among the ranchers.

19.4.2.4 Production of Bio-Oils from Agricultural Wastes

Fundamental oils utilized in arrangement of different beauty care products are additionally acquired from weed plants like Vetivar and so on, whose immense utilization can handle the joining of weighty metals like lead, mercury and so on and other poisonous synthetics in the makeup. Oils extricated from the Cyperus nuts are additionally utilized as pith in agarbattis and so forth.

19.4.2.5 Use of Crop Residues as Animal Feed

In the wake of reaping the leftover yield deposits for the most part straw are gathered and afterwards customarily used as creature feed (IARI 2012), husks from paddy factories can be blended in with different oil cakes got after oil extraction can be utilized as poultry and fish feed. Ranchers additionally blend not many oil cakes alongside straw and other green grain, molasses, and so on in steers feed, this aide in superior soundness of the cows and consequently likewise helps in getting more milk creation. Consuming of yield deposits is one of the primary worries at present day of farming. For crop buildup the board, consuming is one of the simplest techniques and usually rehearsed by the ranchers to save time, and cash as the ranchers need to free the field for arrangement from seedbed for the following harvest (Kaur et al. 2019). So it is smarter to take care of the steers with the buildup after gathering of the harvested product. This will serve for decreasing the natural contamination and simultaneously offer advantages to the dairy cultivation and rearing of animals in the local area.

19.4.2.6 Use of Crop Residue as Bedding Material for Cattle and Roof Thatching

The harvest buildups, for example, straw and so on, notwithstanding being scorched in the field and causing ecological contamination can, on the other hand, be utilized as bedding materials in steers sheds giving a reasonable space to the steers stay (Lohan et al. 2018). They can likewise be utilized as a potential rooftop covering material (Meshram 2002). The squanders gathered from rooftop covering and cows-shed sheet material can again be reused for biogas or other biofuel sources and potential fertilizer making also.

19.4.2.7 Crop Residue Usage for Cultivation of Mushroom

Yield buildups, chiefly paddy straw, can be used as a crude material for the development of different Mushroom species like *Agaricus bisporus, Volvariella Volvacea and Pleurotus spp.* 300, 120–150, and 600 g individually of these mushrooms can be gathered from one kg of paddy straw (Gummert et al. 2020). These mushrooms can likewise be developed on a wide scope of farming squanders viz., groundnut husk, oil palm bundle waste, cotton or wood squander, dried banana leaves as the substrate.

19.4.2.8 Use of Crop Residue in Fibre and Paper Production

Wheat straw blended in a proportion of 60:40 with paddy straw is utilized for paper creation. Sugarcane buildup left after juice extraction is another potential paper making bioresource. Filaments separated from weeds like *Typha, Parthenium, Vetivar, Khimp - Leptadenia pyrotechnica,* and so forth can be utilized generally for different creative purposes.

19.4.2.9 Utilization of Wastes from Poultry Farm

Excreta from poultry homesteads can likewise be gathered and utilized in different above-noticed fertilizers. Winged creatures litter additionally assumes a decent part as fish takes care of and appropriate reusing can likewise help in building up a decent coordinated cultivating framework.

19.5 Precision Input Management for Minimizing and Recycling of Agricultural Waste

19.5.1 Principle and Concept of Precision Techniques in Agriculture

Introduction of precision techniques in modern agriculture could guide us to a productive yet sustainable future as these techniques are potent enough to augment productivity and net return of farms without imparting any negative influence on the environment (Earl et al. 1996; Zhang et al. 2002; Andreo 2013; Lowenberg-DeBoer 2015; Mani et al. 2021). Such techniques are usually site-specific and could results in long-term alteration based on the condition prevailed in that particular site (Andreo 2013; Lowenberg-DeBoer 2015). Precision agriculture (PA) is mainly a combination of systems that integrates ample information, pertinent technology, and suitable management practices. Development of precision techniques and their implications in agriculture were started back in the 1980s while their commercial availability could be recorded from the early 1990s (Finger et al. 2019). In the modern world, PA has transformed the conventional crop and soil management practices to refined and advanced management where space and time-specific changes are taken into consideration even within the same field (Mulla et al. 1996). In a nutshell, this is a refinement of entire field management in which decisions are made in accordance with the variability of resources and situation. According to Patil and Bhalerao (2013), the statistical representation of PA could be made through the equation, $P = 1 - SD$; where $SD =$ standard deviation. If $SD =$ zero, then $P = 1$, which suggests a greatly homogeneous field and P will be 0, if $SD = 1$, which would indicate most variable field.

The principle of PA mainly pivots around the concept of maximization of quality as well as quantity of outputs through efficient utilization of inputs where spatial and temporal alterations within a field are taken into account which in turn results in a lower degree of agricultural waste as well as environmental sustainability. According to Khosla (2008), “right quantity of inputs” at the “right place” at the “right time”, from “right source” with “right manner” are the five crucial “R” factors for effective PA. The concept of PA treats the field as a heterogeneous entity based on which specialized and selective management practises are taken into account (Aubert et al. 2012). Precision techniques could be employed to a broader aspect and are beneficial for all farms whether it would be small or large, conventional, or organic and even applicable for developing farms along with developed ones. Along with the farming of field crops and vegetables, use of precision techniques is gaining popularity in the domain of livestock farming and aquaculture also (Wathes et al. 2008, Berckmans 2014, Busse et al. 2015).

Equipment and farm machinery available for PA are capable of several management practices including tillage, sowing, transplanting, physical weeding, fertilizer application, application of pesticides through sprays, etc. Such types of machinery and equipment form a systematic chain process that ultimately results in a precise operation in the farm (Fig. 19.4). In recent times, particularly in case of developed countries, one of the most widely accepted technology in PA is global navigation satellite system (GNSS) that guides machinery used in farms (Heraud and Lange 2009). Such guidance systems automatically control the functions of farm machinery that eventually lower the loopholes in management practices by overlapping the predefined paths. Several aviation platforms are usually involved for guiding farm machinery through visual feedbacks in the form of graphical outputs or light bars. In this way, presently, the auto-guidance systems could run farm machinery for a particular specialized operation without any direct input from operators (Gebbers and Adamchuk 2010).

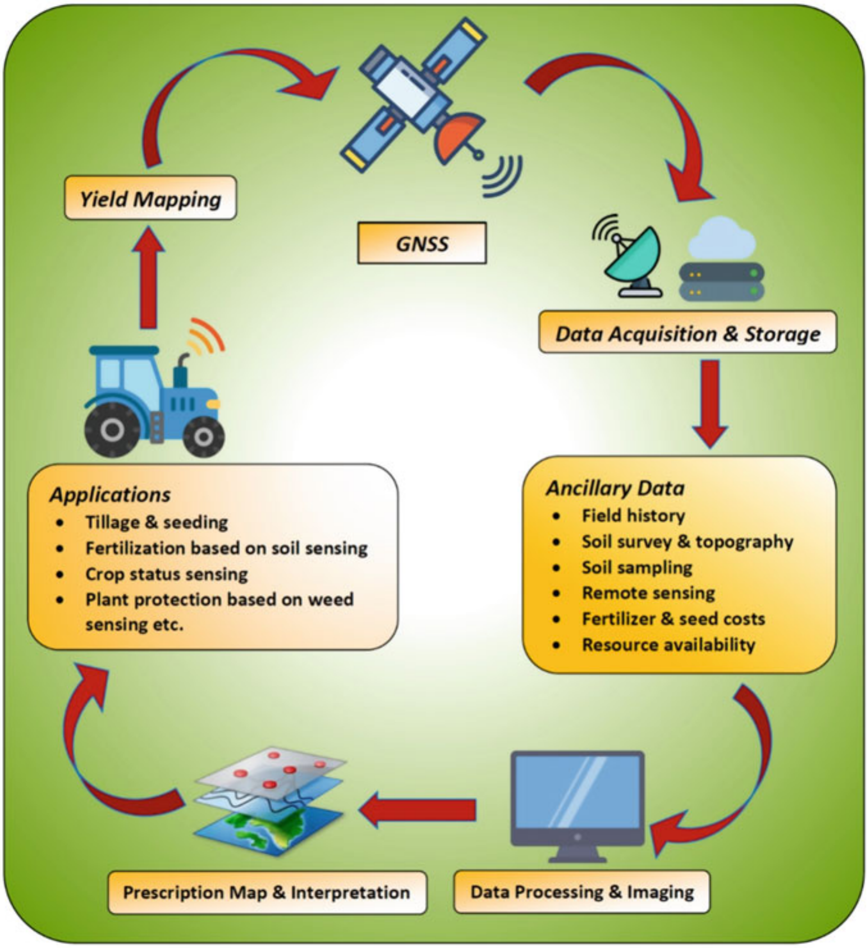

Fig. 19.4 Schematic diagram depicting workflow of precision agriculture (Prepared by Agniva Mandal)

19.5.2 Components of Precision Agriculture

19.5.2.1 Remote Sensing Technique

Remote sensing (RS) could be referred to as the branch of science that acquires information regarding objects under study, from a distance, without actually being in physical contact with it (Moran et al. 1997; Pinter et al. 2003; Atzberger 2013; Lillesand et al. 2014). Sensors are involved in RS techniques that gather the radiations reflected from the target object and the sensors are usually attached to an aviation vehicle like a balloon, an aircraft, and satellites or are even attached to a stand in ground stations. Such sensors are usually associated with different spacecraft as well as aircraft imaging systems among which *Satellite Pour I'Observation* *de la Terre* (SPOT) (i.e., French National Earth Observation Satellite), IKONOS, Indian Remote Sensing Satellites (IRSS), etc., are some renowned spacecraft imaging systems. Precision techniques with the help of RS are generally considered as a potent one to employ in agriculture as it is capable of effective high-resolution monitoring of temporal and spatial changes (Hanson et al. 1995; Moran et al. 1997). However, disadvantages are also there regarding mapping using data obtained from RS. The notable constraints are atmospheric correction, instrument calibration, and neutralization of off-nadir effects in case of optical data. Along with such restrictions, particularly in case of several airborne cameras, data and image processing during cloud screening at the time of monsoon also create limitations for optical RS (Moran et al. 1997). Availability of economically feasible remote sensing techniques need to widen its applicability particularly in developing countries. Along with this, the simplicity of analytical products would also play crucial roles in creating interest among the users of agricultural field (Ray et al. 2010; Sahoo 2011). To develop a well-optimized and acceptable system in PA, a RS technique should possess:

- Lower turnaround time (24–48 h).
- Lesser information cost (~100 INR/acre/season).
- Higher spatial resolution (minimum 2 m multispectral).
- Higher spectral resolution (<25 nm).
- Higher temporal resolution (minimum 5–6 data per season)1.

19.5.2.2 Geographic Information System (GIS)

Geographic Information System (GIS) is a technique having a computerized system that stores and retrieves data according to need and is capable of managing and analyzing spatial data. Provision of detailed maps from GIS using analyzed data eventually help in acquiring better perceptions regarding yield and growth factors of different crops, soil fertility, and pest and weed characteristics also. Such kind of maps facilitates and improve spatial and temporal decision-making systems. Nowadays various GIS soft-wares with a wide range of performance and affordability are available commercially. Several farm information systems (FIS) are there having simple programs capable of producing databases at farm levels. Local Resources Information System (LORIS) is also there which is mainly a FIS having a number of modules that could import data, generate raster files with the help of various gridding methods, form raster database; create digital agro-resource maps as well as operational maps also (Schroder et al. 1997). A complete farm GIS usually provides base maps of land topography, soil type, N, P, K, and other nutrients, soil moisture, pH, etc. Both the soil fertility maps as well as weed and pest intensity maps could be prepared using GIS-based on which further recommendations are generally made for inputs application that reduces the wastage. The data regarding crop rotation, tillage, yield, application of nutrients and agrochemicals could also be stored in the system.

19.5.2.3 Global Positioning System (GPS)

In simple words, a global positioning system (GPS) is mainly a satellite-based system that could navigate any particular position on the earth (Lee 2009). Continuous (24 h in a day) real-time monitoring and navigation of locations through analysis of three-dimensional data over time could be achieved through GPS. Primarily the development of GPS was made to use it in the military, later since the 1980s civilians were allowed to use GPS that gradually facilitated development in spatial data analyses. No charges for subscription or setup are required for using GPS and accession could be made by anyone with a tracking system and could be used in applications that need coordinates to navigate locations. Nowadays it became useful to farmers especially in the case of site-specific operations. Several satellites are associated with GPS-system that identify the exact position of equipment within the farm with minimal error. However, degradation in the GPS accuracy in case of detection with autonomous navigation through single-receiver mode could be possible due to different types of errors. Differential global positioning system (DGPS) is actually the GPS where the operations are made through a differentially corrected positioning mode capable of providing the greater extent of accuracy which is highly needed in PA. Yield mapping and variable rate application (VRA) are the two main operations of PA where DGPS is notably used. A precise location in the field could be determined well using GPS for monitoring spatial variability based on which site-specific precise applications of inputs could be made. The GPS could provide about 20 m of positional accuracy and 1 m of while sub-meter positional accuracy could be achieved in case of DGPS. Incorporation of all field-based variables like yield, soil moisture content, weeds, and pest intensities could be made through successful incorporation of GPS and especially DGPS in farming practices.

19.5.2.4 Variable Rate Techniques (VRT)

Variable-rate technique (VRT) is a combination of systems capable of alteration in the application rate of seeds, fertilizers, irrigation, agrochemicals, etc., across the field based on soil status and site-specific needs. Based on soil status and problems, adjustments in seed rate, applications of pesticide, herbicide, nutrients and lime could be made in an area-specific way (Adamchuck and Mulliken 2005). The VRT comprises a control system equipped with tools capable of variable rate application of inputs based on spatial and temporal changes. Variable-rate nutrient or pesticide application (VRNA or VRPA), variable rate seeding or tillage application (VRTA), and variable rate irrigation (VRI) are the notable management practices commonly used in PA (Diacono et al. 2013). According to Sylvester-Bradley et al. (1999) in case of pre-identified large heterogeneity and predicted treatment zone the VRT is most suitable. However, the insufficiency of pertinent sensors is a troublesome issue (Goulding 2002) in VRT. Murrell (2004) found rise in N use efficiency (NUE) in case of N applications in variable rates as compared to applications in fixed rates, but enhancement in yield was not observed. But, farmers exhibit more interest in practices capable of enhancing both the yields and NUE (Murrell 2004; Olesen et al. 2004, Goulding et al. 2008). Hence, the inclusion of well-optimized VRT is of utmost importance in PA.

Components of VRT

The VRT comprises of many technical units (Fig. 19.5). Principal components of a simple map-based VRT usually includes application software equipped cab-computer controller, an actuator that follows the direction made by the computer that eventually governs the application rates of inputs and a DGPS receiver for geo-referencing that provides information regarding the actual vehicle position. The computer after receiving the location data through DGPS runs the application rate needed at a particular position of the vehicle by synchronizing with several other preexisted information and after that conveys a set-point signal to the controller to regulate the input application at a required rate. The VRT could also record and store the actual rate of application for a particular GPS location that could be used further in future for recommendation purpose (Sokefeld 2010).

Variable Rate Application (VRA) Methods

Based on the use of GPS-system associated with it, VRA methods could be classified into map-based VRA and sensor-based VRA.

Map-Based VRA

In order to control the application rate, the GPS that is present in this kind of VRA usually uses a prescription map which is mostly an electronic map. Actually, a prescription/electronic map is a map having data related to the rate of inputs based on the demand of specific sites of fields. Alteration in input concentration occurs with the applicator movement to meet the requirement of a particular position based on the position detail obtained from DGPS receivers. Maps prepared on the basis of previous measurements are generally considered in case of map-based VRA and suitable strategies are then taken into account depending on information regarding crops, soils, and location under study which includes crop yields, land topography, soil characteristics, RS data sets, etc. (Grisso et al. 2011).

Sensor-Based VRA

In this case, instead of GPS or prescription maps assessment of traits of soils and crops are made with the help of sensors associated with the applicators and then the transfer of the report to the control system is done where input rate calculations are performed. After that transfer of computed information regarding input rate from the control system to the controller is performed depending on which site-specific final applications of inputs are executed. Involvement of real-time data due to the use of

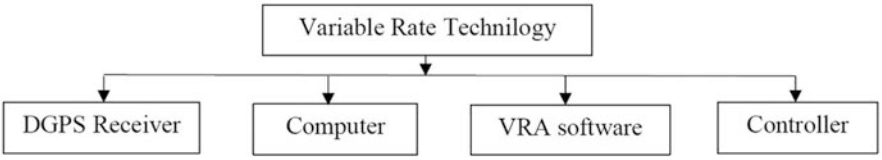

Fig. 19.5 Principal components of VRT

real-time sensors makes the sensor-based VRA superior as compared to map-based VRA (where previously collected data are used).

19.5.3 Applications in the Real World

Regulation of GHGs emission is a serious concern in recent days to combat against the detrimental effect of global warming (Smith et al. 2008; Balafoutis et al. 2017). Apart from the emissions as a result of fossil fuels burning in agricultural machinery mismanagements in fertilizer use, cropping systems, and land use planning are some of the prime reasons behind significant GHGs emissions (FAO 2001; Bouwman et al. 2002). Employment of PA could significantly reduce emissions of GHGs by providing the most suitable management recommendations based on the efficient decision support system (Balafoutis et al. 2017). Improper or excessive application of nitrogenous fertilizers could significantly hasten GHGs emissions in the agricultural sector through the release of N_2O (Eory and Moran 2012; Wood and Cowie 2004; Bentrup and Paliere 2008; Schepers and Raun 2008). In such cases, PA has been found effective in reducing N_2O as well as CH_4 (in case of manure application) emission by regulating the timing and amount of N fertilizer applications (Bates et al. 2009; Eory and Moran 2012; Balafoutis et al. 2017). Bates et al. (2009) found about 5% plunge in GHGs emissions without hampering the yield under VRNA. Under the combined application of VRNA and GPS regarding nitrogen application in fields, Sehy et al. (2003) found nearly 34% decrement in N_2O emission in low-yielding areas. Machine guidance equipped with high-accuracy GNSS receivers could be used in almost all kinds of farm operations including tillage, seeding and planting, weeding, spraying of pesticides, harvesting and threshing, etc., which eventually would reduce the GHGs emissions due to burning fossil fuels in agricultural machinery (Abidine et al. 2002; Bora et al. 2012). Machine guidance actually enhances pass-to-pass efficiency while reduces application gaps and overlapping and could be applied in case of a wide range of VRAs (Abidine et al. 2002). In addition, due to precise application under well-optimized decision support systems, reduction in the use of agricultural inputs (e.g., seeds, fertilizers, manures and agrochemicals for plant protection) under machine guidance would ultimately result in a lesser degree of agricultural waste generation. Alongside, Evans et al. (2013) found that advanced optimized site-specific irrigation system coupled with computer simulation studied could save upto 0–26% water as compared to conventional irrigation. Sadler et al. (2005) also observed around 8–20% reduction in irrigation water use under variable rate irrigation (VRI) system. Thus, by lowering the need for irrigation water VRI could effectively abate the extent of GHGs emissions by eventually reducing the needs of pumping energy.

Monitoring of soil carbon content through remote sensing and carbon mapping is another effective way to mitigate GHGs emissions as well as soil carbon loss and land degradation (Angelopoulou et al. 2020). Though such monitoring reports the present situation of a large area could be analyzed in a short period of time and based on which suitable manage practices (tillage, residue management, fertilization and manuring, the inclusion of effective land uses, etc.) could be performed to sequester C in the soil for a longer term (Mandal et al. 2020). On the other hand, a notable section of farmers follows in situ residue burning mainly to prepare the field and make it available for planting the next crop leading to potentially detrimental effect on both human and animal health, towards the environment and soil fertility and quality as well for a long run (Hiloidhari et al. 2014; Shyamsundar et al. 2019; Dhaliwal et al. 2020). The issue of on-site burning of surplus crop residues is becoming a great concern in present days due to a number of factors including reduced availability of human labour, costly available conventional techniques to remove surplus residues and use of combines, especially in developing countries for crop harvesting. But these crop residues could be utilized as feeds of animals, bio-manure, as soil mulch, for thatching and in some cases for making homes in rural areas and as fuel in industrial as well as domestic use (Bannari et al. 2006; Shyamsundar et al. 2019). In modern days, remote sensing and UAV could be introduced as potent tools for monitoring residue covers over an area of considerable size in a very short time based on which suitable management and recycling of such excess residues could be made (Xiang and Tain 2011; Zheng et al. 2014; Vega et al. 2015; Jannoura et al. 2015). Bannari et al. (2006) also found the data from hyperspectral remote sensing and IKONOS effective in estimation and mapping of soil residue cover over a large area where the hyperspectral data performed better than IKONOS data as because of having enhanced spectral band traits which were sensitive to the crop residues (based on cellulose and lignin absorption features of plants). Recently Kavoosi et al. (2020) studied crop residue cover with the help of drone imagery and Landsat 8 OLI imagery and found slightly more accurate data in case of Landsat 8 OLI imagery while lower expenses, easy access, greater spatial and temporal resolutions and more control over desired data range made the drone imagery advantageous over Landsat 8 OLI imagery.

Generation of a notable portion of solid wastes from the agricultural sector is a great concern (UNEP 2015) and many of which could be served as a precious resource in presence of an efficacious waste-to-resource cycle. The traditional collection of wastes following a schedule is comparatively costly and inconvenient as greater frequency of collection results in wastage of manpower, fuel, and time while the collection of wastes in a less frequent manner leads to overflow of bins, nuisance, and illness in human and animals (Ramson and Moni 2017). Smart waste management system equipped with Internet-of-Things (IoT) could improve the management and recycling efficiency of wastes through advanced monitoring of waste loads and improvising the route of the waste collection also. Modern IoT-enabled sensor networks and cloud computing are capable of providing real-time data, offers advanced monitoring, predictions, decision support system (Ojha et al. 2015; Bong et al. 2018). Such advantages are the reasons behind its increasing popularity environmental as well as agro-industrial sectors, PA and ecological monitoring, restaurant food waste management, and waste collection in smart cities (Anagnostopoulos et al. 2015; Talavera et al. 2017; Wen et al. 2018). In a case study of Suzhou, China around 20.5% increase in the waste collection has been observed in smart waste management system using radio-frequency identification

(RFID)-tagged "smart" bins, automatic weight sensors and collection trucks equipped with an integrated circuit card reader as compared to traditional waste collection (Wen et al. 2018). Bong et al. (2018) are also hopeful for more efficient waste management if incorporation of such RFID-tagged "smart" bins, GPS, automated weight sensors and smart trucks could be made in modern agriculture.

19.6 Challenges for Minimizing and Recycling of Agricultural Waste

In recent times, agricultural residue management for natural agriculture with sustainable and continuing progress has become a topic of huge concern for policymakers (Hai and Tuyet 2010). Huge and unidentified quantities of agricultural residues have always been a major concern and hindrance in agricultural waste utilization and management (Yilmaz 2014). The problem of disposal and further utilization emphasis on the agricultural residues, outdated technologies, poor agricultural mechanization, delayed laws, policies, protocols, and community service arrangements in the utilization of agricultural residue (Nguyen et al. 2014). The major challenges for minimizing and recycling of agricultural waste may be discussed as follows.

19.6.1 Poor Technologies of Converting Agricultural Residue into Biogas

Agricultural residue conversion through the anaerobic method is usually considered the most important and prevalent technology till date worldwide. This technology offers significant and vital advantages to convert several agricultural scums and residues into fertilizer and biogas. Instead of this, there are numerous issues which are still not resolved: crops with high energy were preferred more than local agricultural residues as main feedstock for anaerobic digestion reactors, which is also decisive in unintended landuse alteration (Njakou Djomo et al. 2015). Further, lignocellulosic rich waste has a low economic value of biogas and poor application of anaerobic digestion. The anaerobic digestate of agricultural reuse as possible renewable fertilizer (Bolzonella et al. 2018) may have hygienic as well as environmental hazards which need more in-depth research in future. Sustainable production of biogas through agricultural surplus and livestock waste is not even an easy task for the farmers to achieve at their level.

19.6.2 Development of Building Blocks and other Items

Advance technologies and comprehensive knowledge about the potentialities of agricultural residues befitting with environmental, economic, and societal sustainability is utmost important in the process of biomass conversion. Overcoming the limitations of concocting building blocks and other items in an advanced way from agricultural waste is added hurdles. Proportion of bio-based chemicals (3%) and polymers (2%) (Fiorentino et al. 2017; Aeschelmann et al. 2017) are very much insignificant although the demand for substitution of petro-derived chemicals and building blocks are very high. The foremost limitations of agricultural waste retrieval and conversion into biomaterials and bio-products are mostly connected to consumption of energy, the process of degradation, complex and variation of the chemical composition of agricultural residue, the occurrence of impurities, and lack of awareness and perception of the society. Developing biodegradable plastics, organic acids, or enzymes applications from biomass surplus generate double financial additional value in comparison to generation of electricity, livestock feed and fuel use (Kiran et al. 2015). Conversion of agricultural waste through matching technological approaches and bio-refinery interventions need further development for its sustainability.

19.6.3 Encouraging Agriculture Residue Business for Reuse as Raw Material

The agriculture residues can also be a raw material for some industries and encouraging of these industries is vital. In simple words, it can be stated as agricultural wastes generated from one industrial procedure can be used as the inputs for other industries, which actually reduces the effect of industries in the atmosphere. The concept of an eco-industrial park is a common manufacture and service industries in search of higher ecofriendly and commercial performance with an association in management of ecological and resources issues, also includes energy, water, and materials. Generally, management approaches mostly emphasis on a single final product from a single resource. So, the important known challenge of dealing with the incorporation and integration of agricultural waste business for reuse as input or resources of other industry still exist. Therefore, chains have to be optimized of divergent products and their usage.

19.6.4 Consequences of Agricultural Residue Management Strategies

Ecofriendly management of agricultural residue and also considering the economic challenges for operational methods in particular in the dearth of suitable and early prediction techniques which can be able to give clear pictures to decision-makers or policymakers and also end-users. Life Cycle Assessment (LCA) is a method which is commonly used to measure the effects of products and services on environmental. Even though LCA is pertinent, it is coupled with data limitations (Avadi et al. 2016), indeed data record chain for the agricultural waste which are generally lacking are not easily accessible. LCA is mostly used for a posteriori comparative assessment and the assessment methodology is hence normally assumed unable to guide advanced research and development. Therefore, alternative ways for the estimation of environmental loads in innovative ways of using agricultural wastes needs to be examined. Such incidental estimate in amalgamated forms can be extended to cover areas or rather zones producing fused Territorial Metabolism (TM) LCA or better it can be said that TM-LCA was offered for urbanized areas by Goldstein et al. (2013). Though applicability of LCA and TM and also in combine form thereof stand multidimensional, so it needs a simplified and streamlined approach for providing strong and appropriate advice to pertinent stakeholders and decision-makers.

19.6.5 Knowledge and Awareness about Agricultural Residue Management

Knowledge and awareness about agriculture residue management is also a big challenge to deal with in resolving unsuitable and unequal nutrient supply, pollutants collection, and gathering and also difficulties in agricultural waste transformation. Agriculture developments in many developed countries in the world have incited issues in ecological, technological, and socioeconomical aspects. Soil nutrient diminution arises when exotic food and feed are grown, whereas these nutrients are found in huge amount in livestock raising tracts. Areas in which agricultural waste transformation approaches have been executed like producing of biogas, specified produce usually replace agricultural waste for financial and provide motives stimulated by agriculture and energy strategy activities. Furthermore, agricultural waste transformation methods interrelate with other energies, resources, pollutants, impurities, and cycling of pathogens. So, it is very essential to enhance knowledge, consciousness, and understanding and supports of multisectorial parties concerned.

The various past results have specified that agricultural residues were used in the outdated methods with very poor efficacy for consumption. Sequences of initiatives may be put forward for the positive effect in reutilization of agricultural residues. The initiatives may be as follows: (i) amend and start a lot of policies, laws and protocols in re-utilization of agricultural wastes in a resourceful manner and harmless disposal, (2) increase monetary funding from various networks and improve basic facilities in the utilization of agricultural residue, (3) advance in process of industrial development in the utilization of agricultural residue in order reuse as input or raw materials for other industries, (4) encourage innovative research, demonstrations and extension of proper technologies for utilization of agricultural waste, v) strengthen knowledge and awareness of stakeholders by focusing more in the extension of the recent and appropriate technologies.

19.7 Summary and Conclusion

Agricultural wastage is mostly the leftover residues produced from the growing of raw agricultural produce and also byproducts of the processing industries which may perform beneficial roles. The residues are generally produced from various agricultural and farm activities including, cultivation of crops, livestock rearing, pisciculture, poultry, etc. By managing these wastes by utilizing prior and modern agricultural waste management techniques or systems by following the 3R's principle can be transformed judiciously into user-friendly products. Proper and scientific waste management including collection, storage, treatment, processing, and disposal are key for having better environmental sustainability. Proper waste utilization will not make a greener environment but also lead to viable bioresource generation for the globe.

In farming system need base application of inputs to maintain the ecology, production, and profit are interlinked in the complex way that keeping balance in between these is found to be very hard as focusing on one could hamper others. But the intervention of technology in farming can keep balance in between protecting the environment, maintaining productivity, and increase the profit through efficient utilization and application of farm inputs to a significant extent. Hence precision farming came into foreground using GIS, GPS, from various remote-sensing sensors to geographic information systems are all tools that can help perform numerous applications, such as yield mapping, weed mapping, salinity mapping, and variable rate applications and sensor-based technology using satellite images to quantify the spatial variability with site-specific management. Precision farming is the integration of collecting, interpretation, analysis of data, and implementation of management at a variable rate in proper time and place. The practice of precision farming on large scale as well as the small scale is an economically sound and vertical expansion of production, moreover, input efficient, and less waste-generation technique.

The first and foremost step in precision farming is to identify and measure the variability of the farms. Then according to the variability present in farms management strategies are to be decided. The use of modern agricultural techniques such as precision agriculture involving the use of robotics, software-based smart farming use of modern machinery to exploit and harness more agricultural lands, high-value crop breeding techniques, smart irrigation techniques, climate-smart agriculture not only increase the agricultural productivity but also leads to quality and viability of the production system. With an ever-increasing population, the demands for food production also need exponential growth thereby leading to proportionate waste production and challenges. Thus, it has become very crucial to in the modern era to enhance production in a greener and sustainable manner. However, economic viability for implementation of such technologies is still debatable, but there is no doubt that the future generations will inevitably rely greatly on such management practices. It is noteworthy to mention that the real-time-based continuous acquisition and analysis of decision-making parameters or techniques allow the identification, monitoring, scope for improvisation, monitoring, betterment and optimisation of variables available throughout the supply chain that involves, collection, disposal, and processing and also pre- and post-treatments. Thus, information gathering is an important criterion for decision-making for estimating the cost, mapping of waste disposal pathway, infrastructural facilities, improvisation of available techniques, etc. Thus, promoting and encouraging smart agriculture and resource management of agricultural waste needs to continued parallel in the upcoming future.

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Recycling of Agro-Wastes for Environmental and Nutritional Security

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Pratibha Deka, Sumi Handique, Santa Kalita, and Nirmali Gogoi

Abstract

Agricultural activities generate a huge amount of wastes enriched with potentially valuable compounds. This opens up the possibility of recycling agro-wastes for various purposes. Bulky and perishable nature of agro-wastes always provides hindrance for its storage and transportation. Thus, it demands immediate attention not only to extract the valuable compounds but also to reduce the wastes burden and possible environmental pollution if unattended. Utilization of agro-wastes and reduction of agro-waste induced environmental hazard demands use of efficient technology-specific for an agro-waste. Among different benefits, if recycled, agro-waste provides the soil nutritional security through replacement of mineral nutrients extracted by the crops. In this chapter, we discuss the various environmental implications due to agro-wastes and the possible benefits that can be earned from agro-waste. Use of agro-wastes as industrial raw materials, more particularly for energy production is discussed. Discussion is also made on improvement of soil quality in terms of soil physico-chemical properties, nutrient, and carbon enrichment. Underutilization of agro-waste is one of the major issues in developing countries like India. The hypothesis of the chapter is that utilization of agricultural wastes for crop production can result in substantial reduction of environmental pollution. Knowledge on different application opportunities of these valuable wastes is important to uplift the country's economy and to reduce the pollution.

Keywords

Agro-wastes · Environmental impacts · Energy production · Nutritional security

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Abbreviations

2G	Second generation
AWC	Available water content
Bio CNG	Bio compressed natural gas
CBG	Compressed biogas
CEC	Cation exchange capacity
CH_4	Methane
CO_2	Carbon dioxide
CRB	Crop-residue burning
GHG	Greenhouse gas
HAB	Harmful algal blooms
N_2O	Nitrous oxide
NMHC	Non-methane hydrocarbons
SDGs	Sustainable development goals
SOC	Soil organic carbon
SOM	Soil organic matter
VOCs	Volatile organic compounds

20.1 Introduction

Agricultural wastes or agro-wastes are the waste products generated during different agricultural operations. During different stages of the agricultural production system, ahigh volume of waste materials is generated worldwide (Obi et al. 2016; Kumar et al. 2018). Different agro-wastes include waste from cultivation activities, aquaculture, livestock production, plant waste, agro-industrial waste, and horticulture waste (Prasad et al. 2020). Agro-wastes can be solid, liquid, or gas. It comprises crop waste, food-processing waste, waste generated from animal husbandry, and toxic and hazardous waste. These materials may adversely impact the environment and human health. However, we can also transform the waste into valuable products. The economic values of the beneficial materials obtained from agro-wastes are less than the cost involved in different stages to convert them for beneficial use (Obi et al. 2016).

The agricultural crop residues are of two types, viz. field residues and processed residues. Crop residues are the leftover substances in the fields (agricultural field or orchard) after the harvest; while the processed residues are the materials left after processing of the crop into a usable resource. In India, more than 683 million tons (Mt) of crop residues are generated in a year (TERI 2020). About 178 Mt. of surplus crop residues are left after its utilization as fuel, fodder, and materials in industrial processes. About 87 Mt. of this surplus crop-residues are burnt in different croplands of the country (TERI 2019). Though crop residues have negative impacts on the environment, proper management of field residues can be environmentally beneficial if it is used in improving irrigation, controlling erosion, improving soil aeration, and soil health (Maji et al. 2020).

To feed the global population with shrinking land resources, use of fertilizers, organic manure, and other agro-chemicals to boost the productivity of the farmland are increasing rapidly. This also results in higher production of agro-waste from different agricultural activities. The persistent nature of many pesticides enhances the possibilities of bioaccumulation and biomagnification of these chemicals in the food chain leading to adverse impacts on human health. This demands proper and immediate utilization of agro-wastes and can be achieved by the greater awareness of the farmers and public in proper management and utilization of agro-wastes and thereby protecting the land and the environment (Westerman and Bicudo 2005). Utilization of agricultural wastes for crop production can result in substantial reduction of environmental pollution. This chapter discusses the impacts of agro-wastes on the environment, use of agro-wastes with a special importance on reducing air, water, and soil pollution, mitigating greenhouse gas emission and soil nutritional security.

20.2 Environmental Impacts of Agro-Wastes

Agro-waste may have both beneficial and detrimental effects on the environment. Contribution to greenhouse effect, eutrophication of water bodies, global phosphorus or nitrogen pollution (nutrient pollution), air pollution, climate change, and contribution to ozone depletion in the stratosphere are the main detrimental effects of agro-wastes on the environment (Adegbeye et al. 2020).

20.2.1 Nutrient Pollution

Nutrients are required for the growth of cultivated crops. Organic manure and chemical fertilizers provide the required nutrients mainly nitrogen (N) and phosphorus (P) for plants’ growth and development. And the presence of N and P are a good and simple indicator of nutrient pollution of water bodies (Szogi et al. 2015; Hu et al. 2019; Kumar and Meena 2020). Overuse and underutilization of the nutrients by plants allow its mixing with the surrounding environment. Transportation of the nutrients to water bodies and groundwater deteriorate the water quality. Excessive amounts of nitrogen and phosphorus in the surface water cause eutrophication of water bodies affecting the aquatic ecosystems. Application of synthetic fertilizers, animal wastes, soil erosion during manure application in the agricultural fields, and human wastes are the major sources of nitrogen (N) and phosphorus (P) pollution (Aneja et al. 2012). Some of the major issues of nutrient pollution are formation of harmful algal blooms (HAB), hypoxia, and eutrophication of water bodies (Hu et al. 2019). Formation of HABs may lead to health threats and economic losses (Hu et al. 2019).

Application of animal manure in agricultural fields is a major contributor to the nutrient pollution (Szogi et al. 2015). Soil leaching or runoff of excess manure N and P than the assimilative soil capacity pollute water resources (Szogi et al. 2015). Besides nutrient pollution, animal manure can be a source of pathogens, hazardous metals, hormones, and antimicrobials causing pollution of water bodies (USEPA 2013).

20.2.2 Climate Change

Agriculture and climate change have a strong dependency on each other being the prime source and sink of global greenhouse gas (GHG) emissions (Table 20.1). These gases enhance warming of the earth and act as the main drivers of climate change. It accounts for 10–12% of total GHG emissions of the world (Maraseni and Qu 2016). Agriculture contributed 44%, 25%, 15%, 12%, and 4% of global GHG emission in Asia, America, Africa, Europe, and Oceania, respectively between the period 2001 and 2010 (FAO 2014). Energy use in agriculture contributed another 785 million tons CO_2 eq in 2010 (FAO 2014). Methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) are the main GHGs coming from the agricultural sector (Balafoutis et al. 2017). The largest source of nitrous oxide is agriculture (Reay et al. 2012). GHGs emitted during different agricultural activities are presented in Table 20.1.

In India, 18% GHG emissions are coming from agriculture (INCAA 2010). Vetter et al. (2017) reported farm animals and rice cultivation as the prime sources of GHG emissions in Indian agriculture. They had reported an average emission of 5.65 kg CO_2eq kg^{-1} rice, 45.54 kg CO_2eq kg^{-1} mutton meat, and 2.4 kg CO_2eq kg^{-1} milk. Emission of GHGs from the production of cereals (except rice), vegetables, and fruits are comparatively less. They also suggested an increase of higher emissions of GHGs with the change in food consumption pattern. Emissions of GHGs will increase with more consumption of animal source foods.

Table 20.1 Agricultural activities responsible for major GHG emissions from agriculture sector (Source: IPCC 2008; Mac Leod et al. 2015)

GHGs emitted from agricultural sector	Agricultural activities
CH_4	Paddy cultivation; use of organic manure; animal husbandry
N_2O	Application of synthetic N fertilizers; animal husbandry
CO_2	Mechanical agriculture; different land use and land use changes due to growing different plants

20.3 Air Pollution

Emission from crop-residue burning (CRB), chemicals sprayed in agriculture, farmland, etc. significantly contribute to air pollution. Crop residue burning generates a huge volume of fine particulates and gases including GHGs, CO, NH_3, NOx, SO_2, non-methane hydrocarbons (NMHC), Volatile organic compounds (VOCs), etc. (Jain et al. 2014; Kumar et al. 2021). Favorable weather conditions along with the high intensity CRB may trigger pollutants built up in the atmosphere. For example, in India researchers reported a link between CRB and elevated levels of gaseous and particulate pollutants (e.g., Mittal et al. 2009; Kharol et al. 2012; Ravindra et al. 2019). The intense pollution episode of Delhi, the national capital of India in winter is linked to CRB (Agarwala and Chandel 2020).

20.4 Soil Pollution

Application of chemical fertilizers in farm lands may lead to the alteration in physico-chemical and biological properties of soil (Arévalo-Gardini et al. 2015). Chemicals present in agro-waste may adversely impacts the soil health. A huge input of chemicals (fertilizers and pesticides, hormones, and antibiotics) in farm animals along with the use of contaminated wastewater in farm irrigation influence soil pollution (Saha et al. 2017). Even many of these chemicals are contaminated with harmful heavy metals like arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), zinc (Zn), etc. (Saha et al. 2017 and references therein). Use of contaminated water in agricultural land may result in the buildup of metals like As, Se, etc. (Dhillon and Dhillon 2003; Sharma et al. 2016). Besides building up of toxic chemicals in the fields, chemical fertilizers, and pesticides also destroy the beneficial microorganisms of soil (Önder et al. 2011; Meena et al. 2020; Upadhyay et al. 2020). Agro-waste also enhances soil erosion and sedimentation (Maji et al. 2020) (Fig. 20.1).

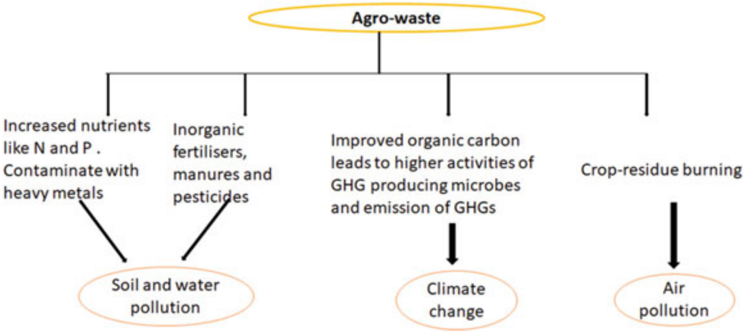

Fig. 20.1 Negative impacts of agro-wastes on the environment

20.5 Agricultural Wastes for Environmental Benefits

The agricultural wastes may be modified for environmental benefits. They can be utilized as energy sources to yield biomass, that produce fuels, heat, electricity and many raw products of industrial and commercial value. They can also be used as food additives and nutritional supplements. Biofuelsare carbon neutral and help lessen carbon dioxide emissions (Hanaki and Portugal-Pereira 2018). Therefore, they play a significant role in reducing climate changes. They are good adsorbents and can remove heavy metals present in the aqueous media. Studies have shown that shells of peanut, walnut, rice straw, sugarcane, and other such waste can be employed to remove lead while wheat and rice bran can be used to remove cadmium (Sabir et al. 2021).

20.5.1 Source for Energy Production

Energy derived from alternate sources like agro-waste may provide means for growth in the economy and meeting energy demands (Omer 2010). Chief sources of energy that can be obtained from agricultural waste are biofuels and biogas. These are renewable sources of energy. These can help in mitigation of climate change and have varied uses (Souza et al. 2017). An example of a biofuel is ethanol which has less harmful effects on man as compared to fossil fuels and significantly lowers emission of GHGs (Chum et al. 2015). Use of such biofuels can increase the carbon content of soil and reduce heat through evapotranspiration (Berndes et al. 2015).

20.5.1.1 Biofuel Production

Agro-wastes yield biofuel. These can be utilized to produce biogas and syngas by anaerobic digestion as well as gasification respectively (Fig. 20.2). They can also be used directly through combustion.

In the transportation sector, biofuel derived from agricultural wastes satisfies the huge demand in renewable energy in the present times. It is used as biodiesel, bioethanol, or bio-jet fuel in liquid form or in gaseous form as compressed biogas. The most extensively consumed liquid biofuel is ethanol mixed with gasoline. Bioethanol constitutes the major sustainable fuel, in liquid form to power motorized vehicles. It can reduce the pollution and lower oil consumption.

Ethanol can be produced from sugarcane and corn by fermentation. Oils from vegetables and animal fat yield biodiesel. Bioethanol may be processed from numerous agri-crop remnants especially those possessing abundant lignocellulose biomass (Saini et al. 2015). Our dependence on forest woody biomass has been reduced due to production of such alternate energy sources. This has played a significant role in decreasing deforestation. Bioethanol from vegetable waste can be produced using *Saccharomyces cerevisiae* in the fermentation process. Hence, the environment will be cleaner as the agro-waste would be utilized to produce bioethanol or other sources of energy.

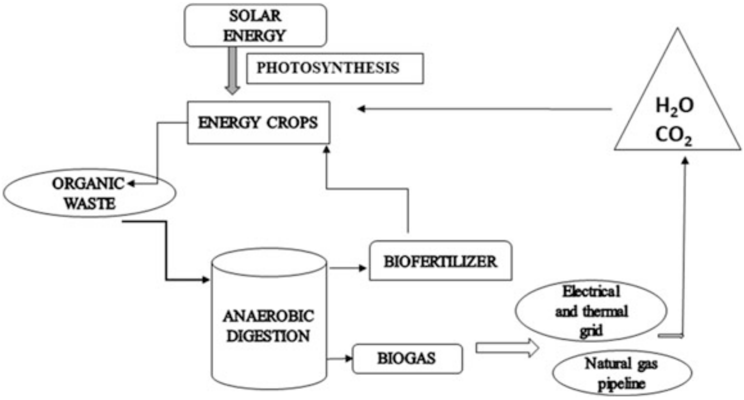

Fig. 20.2 Production of energy from agro-wastes (Data source: https://biogas.ifas.ufl.edu/digesters.asp)

20.5.1.2 How does Biomass Generate Energy?

The energy obtained from biomass feedstocks is bioenergy (Adams et al. 2017). Feedstock is biomass that is used as the source of energy that can generate electricity or used in cooking and heating. These can be obtained from wastes of food processing industries or agriculture. **Various Technologies for Producing Biofuel:** Bioenergy consists of fuels that exist in liquid, solid, or gaseous state. Agro-waste gasification, liquefaction, solidification, or power generation technology may be used to derive energy from such wastes (Lam et al. 2015; Chum et al. 2015).

The conventional first-generation biofuels are synthesized from molasses, sugarcane juice, or syrup (feedstock consisting of sugar), from corn (feedstock consisting of starch) and from oil extracted out of vegetables. The biofuels included in the first generation are obtained through distillation, fermentation, and transesterification (Chaudhari 2019). The second-generation biofuels are processed from straws of rice, wheat, paddy, etc. (feedstock consisting of lignocellulose). Besides obtaining fuel grade ethanol, biochemicals, biofertilizers, liquid carbon dioxide, bio-CNG is also yielded (Chaudhari 2019).

Bioenergy Products: Agro-wastes can be used to generate compressed biogas (CBG). Products like syngas, bio-oil, bio gasoline, biochar, bioethanol, biohydrogen are also produced. Various microbes are used to produce organic acids like lactate, pyruvate, citric acid, oxalic acid, and levulinic acid. Also, such biochemical conversion technology yields butanol, isobutanol, acetone, mannitol, and several products (Chen and Wang 2017).

Conversion Technologies: There are three types of processes to convert biomass to energy. These are physical, chemical, and biochemical conversion technologies.

A. The physical conversion technologies include direct combustion processes and co-firing. The latter is a process of using fossil fuel like coal with biomass feedstock.

B. Thermochemical processes include pyrolysis, carbonization, gasification, catalytic liquefaction.
C. Biochemical processes: Utility of microorganisms to yield ethanol has been in practice since ancient times. Microbes are used to convert wastes to useful compounds. Advances in microbiology and biotechnology have played an important role in energy production from agro-wastes.

20.5.2 Raw Materials for Industries

The wastes generated from agriculture are rich in proteins, carbohydrates, and minerals. They act as “raw material” in formation of products and developments for other industrial processes (Sadh et al. 2018). As they are nutrient-rich, they are a suitable medium for growth of microorganisms. Their reuse helps to decrease pollution and cost of production too, as there is recycling of waste. The wastes from agriculture through a process of solid-state fermentation (SSF) can yield various compounds like enzymes, vitamins, antibiotics, antioxidants as well as biofuels, biofertilizers, animal feed, etc.

Solid State Fermentation: This technique allows organisms to grow on solid substrates or non-soluble material. This is done in limited presence and also in complete absence of free water (Bhargav et al. 2008). Wheat, rice, corn, barley, leguminous seeds, straw, wheat bran, and other such materials are used as substrate. Numerous quality-enhanced commodities can be obtained and different organic wastes can be employed in this process (Pandey et al. 2000; Wang and Yang 2007).

Antioxidant Production: Antioxidants protect us from cancer, asthma, anemia, ischemia, aging dementia, and joint pains. It has been reported that antioxidants that are natural, help in treating virus, cancer and are anti-inflammatory as well as protect the liver (Nigam et al. 2009). Rice, peanut, medicinal plants, crop residues, pineapple, orange, lemon, and pomegranate peel waste can be employed to obtain antioxidants. Wastes like peels of vegetables and fruits are raw material that can be used to yield products having pharmaceutical value (Parashar et al. 2014).

Antibiotic Production: Antibiotics like oxytetracycline can be produced from agricultural residues like rice hulls, sawdust, and corn cobs (Ifudu 1986). Using these residues help to reduce the expenses involved in production of antibiotics.

Enzyme Production: Agro-wastes can yield enzymes on fermentation. An example is amylase that helps in breaking complex carbohydrates to simple sugars. (Nigam and Singh 1995; Akpan et al. 1999). Enzymes like endoglucanase and β-glucosidase were obtained from different agro-wastes (Kalogeris et al. 2003). Enzymes produced from miscellaneous agro-wastes are given in Table 20.2.

Apart from the above-mentioned utilizations, agro-wastes are also employed for the production of edible mushroom, oncom and tempeh which are nutrient sources.

Table 20.2 Enzymes produced from agro-wastes

Enzymes obtained	Agricultural wastes used as substrate	Microbes used	References
α-Amylase	Papaya waste	*Aspergillus Niger*	Sharanappa et al. (2011)
	Peel of oranges	*Aspergillus Niger*	Sindiri et al. (2013)
	Cake from coconut oil	*Aspergillus oryzae*	Ramachandran et al. 2004)
	Soybean, rice and wheat bran, black gram bran	*Aspergillus Niger*	Akpan et al. (1999)
	Bran from rice and corn	*Bacillus species*	Sodhi et al. (2005)
	Wheat and rice bran, potato peel	*Bacillus amyloliquefaciens*	Mojumdar and Deka (2019)
	Wheat bran and rice husk	*Bacillus subtilis*	Baysal et al. (2003)
β-Glucosidase	Wheat bran	*Aspergillus* sydowii BTMFS 55	Madhu et al. (2009)
Cellulase	Banana wastes	*B. subtilis* CBTK 106	Krishna (1999)
Endoglucanase	Rice bran	*Trichoderma reesei* QM9414	Rocky-Salimi and Hamidi-Esfahani (2010)
Invertase	Waste from peel of fruits	*Aspergillus Niger*	Mehta and Duhan (2014)
Laccase	Wheat bran	*Cerrena unicolor*	Rebhun et al. (2005)
Lipase	Groundnut oil cake	*Candida rugosa*	Rekha et al. (2012)
	Linseed oil cake	*Pseudomonas aeruginosa*	
Protease	Wheat bran and lentil husk	*Bacillus species*	Uyar and Baysal (2004)
Protease and lipase	*Jatropha* seed cake (deoiled)	*Pseudomonas aeruginosa*	Mahanta et al. (2008)
Pectin methyl esterase	Wheat bran and orange peel	*Penicillium notatum*	
Tannase	Palm kernel cake and tamarind seed powder	*Aspergillus Niger*	Sabu et al. (2005)
	Leaves of Amla, Jamun, Ber, Jowar (*Phyllanthus emblica, Syzygiumcumini, Ziziphus mauritiana Sorghum vulgaris,* respectively)	*Aspergillus ruber*	Kumar et al. (2007)
Xylanase	Wheat bran, sugarcane bagasse, rice straw, hulls of soya bean	*Aspergillus terreus, aspergillus Niger*	Gawande and Kamat (1999)

(continued)

Table 20.2 (continued)

Enzymes obtained	Agricultural wastes used as substrate	Microbes used	References
	Peels of oranges	*Aspergillus Niger*	Mamma et al. (2007)
	Palm waste	*Aspergillus terreus*	Lakshmi et al. (2009)

20.6 Agricultural Wastes for Nutritional Security

Agricultural wastes such as crop residues are known to contain high levels of nutrients like phosphorus, nitrogen, potassium, etc. (Sharma and Garg 2019). Thus, agro-wastes can be used to enhance nutritional security, source of nutrients and carbon in soil, sources for improved microbial activity, etc., and can be used as bio-fertilizer and soil amendment. The mineral fertilizers can be decreased by the sustainable use of agro-waste (these mineral-based fertilizers have negative environmental effects, and some of these fertilizers need to be imported (European Commission 2015; Meena et al. 2020a). One of the important methods of mitigating climate change is to ensure resource efficiency and thereby we can attain compliance with many of the Sustainable Development Goals (SDGs) (United Nations Economic and Social Council 2017; Duque-Acevedo et al. 2020). There are abundant opportunities for developing nutritional security by recycling nutrients in a country like India where copious amounts of wastes are generated annually from the agriculture sector. Thus, agro-wastes can be used as environmentally friendly material to improve the source of carbon and nutrients in soil and to favor a framework of minimal waste generation as well as increase the quantity and quality of produce in agriculture.

20.6.1 Impacts on Soil Quality

Soil quality is the basis for sustainable agriculture. Agro-wastes such as crop residues application results in several advantages for agricultural crops such as better soil quality, increased nutrient contents, etc. (Fig. 20.3) (Hiel et al. 2016). If utilized efficiently, these wastes can improve the physico-chemical properties of soil and add to the nutritional value of the soil. Moreover, these wastes increase the soil microbial diversity and thus subsequently the soil health. The organic matter present in these crop residues can also increase the soil organic matter content.

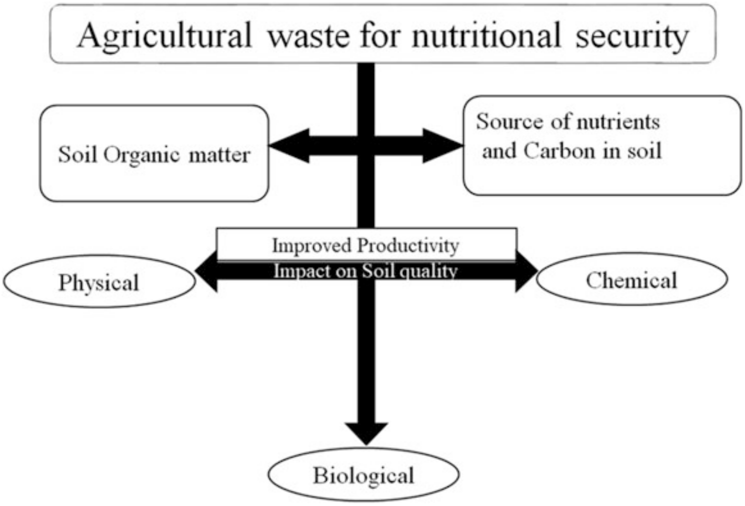

Fig. 20.3 Use of agro-wastes for nutritional security and soil health

20.6.2 Source of Nutrients in Soil

The use of both nutrient-rich agro wastes and mineral fertilizers in crop fields can promote sustainable and ecofriendly agriculture and promote crop productivity (Paul and Mannan 2006). According to reports, this approach reduces the need of chemical fertilizer used in conventional agriculture (Agele et al. 2011; IAEA 2003; Krupnik et al. 2004) and enhances productivity (Dobermann and Cassman 2002).

To increase the quality of agricultural wastes and reduce the toxic contaminant present in the wastes, vermicomposting is one of the promising alternatives where recycling of the nutrients and organic matter provides an environmentally sustainable and ecofriendly solution and also reduces pollution. Composting uses aerobic fermentation methods to change agricultural wastes or any organic wastes into soil conditioner. The compost can be converted into organic fertilizer by addition of minerals derived from natural sources such as rocks to control N:P:K ratio (El Haggar 2005). Researchers are reported to have a preference for livestock wastes (Sharma and Garg 2019) specially in the use of vermicompost as feed material for earthworms (Sharma and Garg 2019). Various studies suggest that vermicomposting enhances the nutrient content in the wastes and increases the organic carbon and C:N ratio. High carbon-to-nitrogen ratio in agricultural wastes increased the nitrogen immobilization process so it can be taken up by the microbes (Singh et al. 2008). Such practice can also enhance biogeochemical cycling of nutrients through improved microbial diversity in soil (Agele et al. 2011) and can possibly improve soil health and reduce pollution. It is reported that the combined use of animal wastes with lignocellulosic material in composting can be used as natural soil conditioners or organic amendments (Yang et al. 2010; Albuquerque et al. 2009).

20.6.3 Source of Improved Soil Carbon

Use of agricultural wastes as a source of organic matter and nutrients in soils can be a good approach to maintain or raise the soil organic carbon and thereby improve soil health (Peltre et al. 2017) through improvement in physical properties, such as stability of aggregates and soil porosity (Annabi et al. 2011; Grosbellet et al. 2011; Schjonning and Thomsen 2013). By supplementing nutrients in soil depleted by crop growth, addition of agro-wastes can help to avoid heavy use of chemical fertilizers and thereby help in combating global warming by decreasing the fuel consumption used in the manufacture of these fertilizers (Diacono and Montemurro 2010). Moreover, this strategy has an added benefit of helping reduce climate change through the carbon sequestration from the atmosphere in the soil (Lal 2004). The use of agro-wastes can help in improving physico-chemical properties of soil such as increase water holding capacity, soil porosity and permeability, percolation of water and also help maintain as well as raise the soil organic carbon (SOC) (Celik et al. 2004; Herencia et al. 2011; Li et al. 2018). These wastes can also decrease bulk density, soil compaction, and crust formation. The repeated application of organic wastes in soil has found to have increased soil porosity and, therefore, decreased the bulk density of the soil (Schjønning and Thomsen 2013; Martin et al. 2009). Agro-wastes also help to build a fertile soil structure by enhancing the soil organic and humid content which can have positive influence on the process of soil aggregate formation and thus make better use of water and nutrients (Candemir and Gulser 2010; Aggelides and Londra 2000; Bronick and Lal 2005; Yadav et al. 2020). Moreover, the variety of crop residues or organic wastes that are used and their decomposition rate influences the rate of aggregate formation. The use of these wastes improve the physical properties of soil (soil structure, water holding capacity, etc.) chemical properties (such as biogeochemical cycling, etc.) and also various biological properties of soil (such as improve soil microbial diversity etc.) (Candemir and Gulser 2010; Gulser and Candemire 2015; Singh et al. 2008; Demir and Gulser 2015). Thus this approach is very beneficial for soil health as well as increasing quantity and quality of produce.

20.6.4 Source of Increased Agricultural Production

The improved bio-physico-chemical properties of soil by the addition of agricultural wastes also increase the diversity of microbes in the soil (Yang et al. 2010) and thus results in increased crop production. Addition of these wastes improve the quality of soil and soil health not by increasing organic matter and nutrient supply and also improving physical, chemical, and biological properties of soil and subsequently improving the quality and quantity of produce (Salinas-Garcia et al. 2001; Schutter et al. 2001; Roldan et al. 2003; Alvarez 2005; Kachroo and Dixit 2005; Blanco-Canqui and Lal 2009; Ludwig et al. 2011; Agneessens et al. 2014). Application of agro-wastes to crop fields is known to improve the biological properties of soil resulting in improvement of the problem of soil salinity. Activities of enzymes urease and alkaline phosphatase along with respiration rate were significantly stimulated by the use of agro wastes in alluvial and marine soils (Mariangela and Francesco 2015). Cayuela et al. (2009) reported that the use of agro-wastes resulted in sustainable management of soil carbon and nitrogen and had positive effects on soil properties including remarkable improvement in soil biological functions (Yang et al. 2010).

Various studies have confirmed the positive results of the use of agro-wastes such as manure from livestock, crop residues, etc., on the crop yield and other plant physiological and morphological features due to improved soil chemical and biological quality. Poppy waste, an agro-wastes and an inexpensive organic carbon source was found to have positive effects on various soil properties as well as increased crop productivity (Yang et al., 2010; Hardie and Cotching 2009).

Application of agro-wastes have reported to have improved soil properties (such as porosity, bulk density, soil aggregates, etc.) (Gülser and Candemir 2015; Demir and Gulser 2015). Soil chemical properties (e.g., available nutrients, cation exchange capacity, etc.), and biological properties (such as soil organic carbon sequestration, soil microbial diversity, etc.) also improved due to addition of agro-wastes (Singh et al. 2008; Candemir and Gulser 2010). Moreover, the presence of crop residues tends to increase hydraulic conductivity and also stabilize soil aggregates (Turmel et al. 2015). The compost from agro-wastes results in addition of important nutrients necessary for crop growth in soil (De Corato 2020; Duong et al. 2013; Evanylo et al. 2008). It also prevents nutrient leaching (De Corato 2020; Grey and Henry 1999), increases soil organic matter (SOM) contents (De Corato 2020; Hemmat et al. 2010), improves soil aggregates (De Corato 2020; Celik et al. 2004) and soil porosity (De Corato 2020; Caravaca et al. 2002) and increases crop productivity (Zaccardelli et al. 2013). Removal of agricultural residues coupled with tillage through conventional practices results in rapid depletion of soil organic carbon in agricultural fields (Yang and Wander 1999; Mann et al. 2002). Increased soil organic carbon (SOC) was reported after application of agro-waste at regular intervals (Blanco-Canqui and Lal 2007; Bhattacharyya et al. 2008; Dhiman et al. 2000; Karanja et al. 2006). Ogbodo (2009) reported significantly higher organic matter content in the soil where rice straw and legume residue treatment was given compared to the soils where no treatment was given. Singh et al. (2004) documented that addition of residue from rice crops in sandy loam soil significantly increased soil organic carbon content in comparison with straw burning or removal of residues. Incorporation of wheat straw treatment raised the organic carbon content as reported in some studies whereas no significant effect of incorporation of rice straw (for a period of 3 years) was noted on soil carbon in a sandy soil (Naklang et al. 1999). Whereas, compared with plant residue removal after one annual cycle, significant increase (28%) in soil organic carbon was reported in a rice-barley rotation under dryland conditions in northern India (Kushwaha et al. 2000). Increased soil cation exchange capacity (CEC) is determined by the proportional increase in soil organic matter content (Mubarak et al. 2003; Abbasi et al. 2008; Abbasi et al. 2009). This increase in CEC improves the available potassium in the soil and thereby potassium utilization by the crops. Availability of soil phosphorus was documented under incorporation of agro-wastes due to direct decomposition or release of phosphorus from crop residue or indirectly increasing the soluble organic matter content (Nziguheba et al. 1998). Singh et al. (2001) and Singh and Sharma (2002) found marginal or no increase in soil available phosphorus where treatment was given with crop straws (wheat and rice). Whereas, long-term treatment with residues from maize crops has found to raise the contents of soil available P and K (Dam et al. 2005).

Biochar (charcoal derived from agro-wastes by pyrolysis) application has been observed to improve the nutrient and soil water retention (Abel et al. 2013; Lehmann 2007; Sohi et al. 2009; Spokas et al. 2012) by increased soil aggregation and promoting mineral adsorption that improves infiltration rate of water in the soil (Major et al. 2012). Biochar's high porosity can improve soil properties such as porosity etc. (Barnes et al. 2014; Uzoma et al. 2011; Herath et al. 2013). Speratti et al. (2017) reported potential increase in soil water retention, plant AWC, and nutrient content after addition of cotton and swine manure biochar unamended soils. Hasan et al. (2016) reported that Bagasse ash with lime addition to expansive clayey soil results in modest effect on the soil strength, but lone addition of bagasse ash results in significant reduction of the shrink-swell capacity of soil.

Almendro-Candel (2018) reported improvement of soil physical property after addition of wastes obtained from vegetables (high quantity of lignified materials) with significant influence on soil properties such as porosity, and infiltration, etc., whereas lesser content of lignified materials improved nutrient availability in soil. Hardie and Cotching (2009) found that application of wastes obtained from poppy crops resulted in improvement of SOC, salinity of soil as well as pH(Yang et al. 2010). Mubarak et al. (2009) studied the residues from agricultural crops, wastes obtained from vegetable markets as well as wastes from livestock and used as treatment for crops and found that almost all organic materials resulted in significant positive effects on soil physical and chemical characteristics as well as accumulation of plant dry matter. These above studies prove that the strategy of application of agro-wastes is very beneficial for soil health and subsequently increasing quantity and quality of produce.

Thus, input of agro-wastes plays a significant role in maintaining soil fertility and nutritional security as thus increase agricultural productivity by providing nutritional benefits to the crops, and also improve activity of soil microbes, maintaining of soil properties and health by improving moisture retention, gaseous exchange, bulk density and buffer capacity (De Corato 2020).

20.7 Conclusion and Future Prospects

Agro-waste has both positive and negative impacts on the environment. Improper management of agro-wastes and over use of chemicals in farm lands lead to environmental degradation. However, transformation of agro-wastes to valuable products and its proper handling can safeguard the environment. As a source of domestic clean energy with least environmental pollution, agro-wastes can reduce the dependence on fossil fuels, generating employment, and thereby, revitalizing rural economies.

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Agricultural Waste Management Policies and Programme for Environment and Nutritional Security

21

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Abstract

Agriculture is the largest contributor to the global economy and only source for the food and nutritional security; which also generates large amount of waste materials. Agricultural waste (AW) is usually comprised of food processing waste (about 20% of maize is canned and 80% is waste), crop waste, animal waste, and toxic waste used in farming operations. Globally, around 998 Mt of AW is generated annually. Every year, in India, around 500 Mt of crop residue is produced; major portion of it used as fodder and fuel. Yet, there is an excess amount of 140 Mt is remained and about 92 Mt is burned annually. Paradoxically, generations failed to recycle or utilize this energy efficiently in agriculture sector. Hypothesis of the present chapter is, reconnecting crop and livestock production, estimating the nutrient flows between crop production and allied sectors aids in

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provision of attaining sustainability in food production system; also, to achieve clean environment. To do so, it is important to consider and promote waste management to recycle the mineral nutrients through agro-industrial processes. Thus, a new global effort is pivotal to create awareness on agricultural waste management (AWM) and draw a new scenario to improve nutrient use efficiency, produce more necessary inputs, simultaneously decreasing the environmental impacts. This chapter aims to highlight various categories of AW and its impacts on environment, potential values and benefits of AW in soil health management, crop production, economy and environmental security and different technologies for AW recycling and utilization options. This chapter also focusses on the necessity of various policy programs to develop the AW management.

Keywords

Agricultural waste · Food security · Environment · Policy programs

Abbreviations

AD	Anaerobic decomposition
AW	Agricultural waste
AWMS	Agriculture waste management systems
BOD	Biological oxygen demand
C	Carbon
Ca	Calcium
CA	Conservation agriculture
CBP	Consolidating bioprocessing
CH_4	Methane
CO_2	Carbon di-oxide
COD	Chemical oxygen demand
CPC	Civil procedure code
CPCB	Central Pollution Control Board
Cu	Copper
dB	Decibel
EEA	European Economic Area
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FDA	Fluorescein Diacetate Hydrolysis
Fe	Iron
FVW	Fruit and Vegetable waste
GDP	Gross Domestic Product
GHG	Green House Gases
GL	Gigaliters
Govt.	Government
IAA	Indole acetic acid

IPCC	Intergovernmental panel on climate change
K	Potassium
LCB	lignocellulosic biomass
LPG	Liquid petroleum gas
Mg	Magnesium
Mm	Millimetre
Mn	Manganese
Mt	Million tons
N	Nitrogen
N_2O	Nitrous oxide
NaOH	Sodium hydroxide
NGT	National Green Tribunal
NH_3	Ammonia
Nm^3	Normal cubic meter
NO_x	Nitrogen oxides
NPMCR	National Policy for Management of Crop Residue
NRSA	National Remote Sensing Agency
NTPC	National Thermal Power Corporation
OC	Organic carbon
P	Phosphorus
PM	Particulate matter
R&D	Research and development
RKVY	Rashtriya Krishi VikasYogna
SHF	Separate or sequential hydrolysis and fermentation
SO_2	Sulphur dioxide
SOM	Soil organic matter
SSCF	Simultaneous saccharification and confrontation
SSF	Simultaneous saccharification and fermentation
SSF	Solid State Fermentation
T	Ton
TS	Total Solid
UN	United Nations
US	United states
USA	United States of America
USDA	United States Department of Agriculture
VOC	Volatile organic compounds
Wt	Weight
yr.	Year
Zn	Zinc
Mm	Micrometer

21.1 Introduction

Agriculture has made great strides in achieving global food and nutritional security over the past years. Production in agricultural sector more than tripled between 1960 and 2015, while enhancing the technologies introduced by green revolution and a significant growth in utilization of available natural resources such as land, water, etc., for agricultural purposes (FAO 2017a). Human well-being is comprised of multiple constituents such as basic materials for a good life, including shelter, health, enough food, clothing, adequate livelihoods, clean air and water, a secured access to natural and other resources. Yet, food is the priority for living, which can be produced only through farming. Agriculture is one of the largest biological sectors which is associated with forestry, dairy, horticulture, poultry, beekeeping, mushroom, etc., generating employment opportunities to youths in the form of processing, marketing, and distribution while playing a critical role in the global economy.

In addition, food and raw materials from agriculture sector providing employment opportunities to a very large population of most of the developing countries. The FAO report *World agriculture at* 2050 projects an annual growth rate of 2.7% to the world economy (Alexandratos and Bruinsma 2012). Accordingly, global gross domestic product (GDP) would increase to US$126 trillion in 2050 as compared to the amount US$50 trillion reported in 2005–2007 (FAO 2017b). The need for improved agricultural production gained importance during the Second World War (1939–1945) to ensure healthy living and proper nutrition of the people worldwide (FAO 1948). However, later, governments prioritized the restoration of the agricultural produce to deal with hunger and malnutrition problems. Since then, agriculture sector has been identified as a major resource to improve the living standards of world's population and to reduce poverty of the developing countries. For around 8000 years, cereal crops viz., rice, wheat, and maize have been the staple food for humans as well as animals worldwide (FAO 2015). The Green Revolution transformed the global agriculture system and introduced the high yielding rice and wheat crop varieties that helped people overcome the poverty (FAO 2004).

For the past decades, majority of the global population predominantly lived in rural areas (> 60%). Today, about 54%, which is more than half of the world population is in urban areas as the living style changed markedly. UN projections say that by 2050, around two-thirds of the population may live in urban areas (UN 2015). In absolute terms, worldwide, urbanization could lead to add around 2.4 billion people in cities and towns by 2050 which leads to a net reduction of nearly 200 million people in rural population (UN 2015). Consequently, urbanization impacts food consumption patterns and increases the demand for more food. Production of food has increased triple over the last 50 years due to land expansion for agricultural purpose: introduction of innovative technologies after the green revolution greatly influenced the productivity to meet the food demand of the accelerated growth of population (FAO 2019). As a result, worldwide, an average of 23.7 Mt food per day is produced by agriculture (FAO 2017b).

Global agricultural production is pressurizing the environment and the quality of soil, air, and water resources (FAO 2017c). Environmental issue such as generation of greenhouse gases (21% of GHG emissions) increase global warming caused by agricultural activity and development resulting into reduction in biodiversity and rise in environmental degradation. Increasing temperature of earth's atmosphere resulting into climate change which leads to several extreme events such as cyclones, floods, droughts, storms, etc. Such vagaries of weather also devastate the agricultural production (Rakesh et al. 2019). Moreover, food production is extremely sensitive to the impacts of weather as driven by climate change as it is highly dependent on natural climate. Furthermore, the ground water pollution caused by excessive usage of chemicals and pesticides will presumably become a growing problem of industrialized and developing countries. Nitrate (NO_3^-) pollution has become a serious issue all over the world. It is estimated that by the end of 2020, global demand for inorganic fertilizer nutrients such as nitrogen (N), phosphorus (P), and potassium (K) will reach 202 Mt with the annual growth of 1.9% (FAO 2017d).

Intensive agricultural activity generates wastes in different forms (solid, liquid, and slurries) and are produced in small quantities in comparison to the other industries, pose to be potential source of pollution in the long run. There has been immense change in animal production system, which has transformed into an enterprise benefitting the farmers. The waste consists of animal drops, urine which contains organic chemicals and pathogens have potential to contaminate the soil, water, and air. The impact of agricultural industry waste also pose threat to environment (Kumar et al. 2018).

This new situation alarming us the need of sustainable development and the important changes required in the current agriculture system (FAO 2016). Addressing the environmental impacts of intensive agriculture is the need of the hour. Development of agriculture practice in a sustainable manner would minimize this adverse impact due to the intensive agricultural practices (Bennett et al. 2014; Kumar and Meena 2020). The proper integration of the livestock with the best management systems of agriculture would increase the efficiency of the different biological cycles and improve the functions of the agroecosystems. Effective utilization of available natural resources and improving use efficiency of the food system can alleviate the food security problems and also ensures the environmental safety.

Agricultural wastes are composed of the materials which are both biodegradable and non-biodegradable. The chemical and physical composition is an important factor for determining the kind of the management systems need to be employed. The waste recycling and management systems would play an immense role in shaping the strategies for reducing the quantity of the wastes and recycle nutrients from the organic materials/wastes in order to mitigate the negative environmental impacts of agricultural production and assure the global food security. Hence, for planning and processing of the agricultural wastes (AW), it is mandatory to identify the sources of the waste generation and identification of the suitable remediation processes for best utilization of these waste materials for the sustainable development and protection of the ecosystems. Hypothesis of the present chapter is, reconnecting crop and livestock production, estimating the nutrient flows between crop production and allied sectors helps in attaining sustainable food production thereby achieving clean environment. Therefore, this chapter focuses on various aspects of AW and its impacts on environment, potential values and benefits of AW in soil health management, crop production, economy and environmental security and different technologies for AW recycling and utilization options as well as the need of policy programs to improve AW management.

21.2 Agricultural Waste Generation and Environmental Impacts

Agriculture creates employment opportunities and develop green markets by converting AW into value-added products (EC 2017). Agricultural waste is generally considered as a liability as there is a considerable gap between the means that can transform it to useful value-added products. The accumulated crop residues and by products in the farm and the processing sites can cause serious management and disposal problems. Some of the common agricultural byproducts that takes a significant amount of time for degradation and produced in quite a large quantity are cashew nut shell, coconut shell, coir pith, bagasse, rice husk, groundnut shell, silk cotton shell, cotton waste, oil palm fiber, and shells (Sugumaran and Sheshadri 2009; Kumar et al. 2021). These are some nonproduct outputs of agriculture production and processing which may bring some economic values but their collection, transportation, and processing costs for converting them into beneficial products is much higher.

It is estimated that agricultural and food industry waste contributes about 30% of the worldwide agricultural production which is quite a significant amount (Sarmah 2009). Agricultural waste includes a broad spectrum of organic residues and inorganic chemicals that are treated as byproducts from agricultural sectors and agro-industries (Meena et al. 2020). Expansion of agriculture has led to generation of increased amount of agricultural crop residues, livestock waste, and agro-industrial by-products. As a result of intensive farming, there is expectation of a significant rise in global agriculture waste generation. As projected, about 998 Mt of agricultural waste is generated annually (Agamuthu 2009). The amount of organic wastes would be around 80% of the total solid wastes produced in any farm (Brown 1997) in which about 5.27 kg/day/1000 kg manure can be produced (Overcash 1973). They are generally discarded by the farmers, as they fetch no direct economic value to them.

Almost any agricultural activities including cultivation of crops, field and horticultural, grazing, dairy farming, fishery, nursery preparation, livestock breeding, and even forestry serve as a source of generation of agricultural waste. The form of the agricultural waste depends mainly on the agricultural activities and they can be solid, liquid, or slurries. The amount of waste generated by agriculture and allied sectors are quite low as compared to other industries. But if they are allowed to be thrown untreated for a longer period, they can be a threat to our resources. For instance, excessive seepage of organic nutrients into the water bodies and spreading in soils can cause pollution of soil and water. The excreta eliminated by animals comprises of harmful pathogens which may act as contaminants in soil and groundwater (Sarmah 2009).

Agricultural wastes can be categorized into two types—generated during cultivation and generated during processing. While agricultural waste can be converted into more beneficial and nutrient-rich composts to enhance soil health, it is very crucial to treat the waste generated during processing, i.e., agro-industrial wastes as they give rise to serious disposal problems (Rodríguez-Couto 2008) and emission of greenhouse gases (GHGs) (Bos and Hamelinck 2014).

21.2.1 Categorization of Agricultural Wastes

21.2.1.1 Agricultural Residues

Major agriculture residues can be divided into two general categories, one mostly consists of residues left in fields and orchards after harvesting (leaves, stalks, seeds, pods, and stems) and alternatively the materials which are the remains of parts after processing (molasses, bagasse, seeds, shell, husks, pulp, peel, roots, etc). Around 2802 Mt of crop residues produced in world annually (Zabed et al. 2016) in which rice straw is produced about 731 Mt (Sarkar et al. 2012); wheat straw is 354.31 Mt and corn stover is 128.02 Mt (Pattanaik et al. 2019). Similarly, barley, jute, sorghum, and oats also used as agriculture wastes. These could be easily processed into numerous value-added products as these are abundant and cheapest source of feedstock.

21.2.1.2 Agro-Industrial Residues

The agro-industry wastes are the byproducts of food processing industries which include fruit pomace after juice extraction, vegetables and fruit peels, starch residues, sugarcane bagasse, molasses, deoiled seed cakes, chicken skin, slaughter house, and meat processing wastes (Pattanaik et al. 2019). The sugarcane bagasse production is near about 180.73 Mt (Saini et al. 2015) and palm oil waste is nearly 35.19 Mt (Sukiran et al. 2017; Yadav et al. 2020) are two major waste producing agro-industries. Other than these, nonedible plant's seeds like Jatropha (*Jatropha curcas)* and Pongamia (*Pongamia pinnata*) also come under agro-industry wastes.

A considerable amount of organic and inorganic effluents is released from food processing industries. They generally have high BOD, COD, and suspended matter and if left untreated they can cause serious damage to the environment and human health. But they reserve the potentiality to be converted to different value-added products that can act as soil amendments, fertilizers, biofuels, and bioactive compounds. At the same time this recycling reduces the excess cost incurred for treatment and disposal of wastes. In case of oil cake industries, after the process of oil extraction the residues left, i.e., the oil cakes are harmful for environment as they comprise of high levels of suspended solids, oil, grease fat, and dissolved solids (Sadh et al. 2018).

21.2.1.3 Fruits and Vegetables

Annually, around 50 Mt of fruits and vegetables waste (FVW) is generated globally (Hardia 2015). In the developing countries, due to the lack of storage and processing, maximum FVW generated during harvesting and processing and only 10% waste generated during the consumption. In developed nations this loss occurs during the harvesting and consumption stages (Espraza et al. 2020). The majority of the FVW are generated from the food processing industries which is generally comprised of apple, grape, sugarbeet pulp, tomato, olive pomace, palm fiber and kernel shells of potato pulp and peelings, and citrus and pineapple peels. In India, Philippines, China, and the USA FVWs generated during the harvesting, processing, packaging, and marketing amount to 1.81, 6.53, 32.0, 15.0 Mt respectively (Wadhwa and Bakshi 2013).

21.2.1.4 Livestock Wastes

Livestock and poultry industries generate waste in three forms—liquid manure, solid manure, and waste water which if remain unattended may become harmful to the environment. Mainly, the waste are the excreta of the animals and their production depends on the diet composition, age and size of the animal and performance of the animals along its husbandry (Ryser et al. 1994). These untreated wastes cause air and surface water pollution. These solid manures have potential to release near about 18% carbon dioxide (CO_2) and 37% methane (CH_4) increasing these GHGs in atmosphere (Holm-Nielsen et al. 2009).

The estimated amount of total agricultural waste generated in 2025 in different South Asian countries have been presented in Fig. 21.1. The highest amount of agricultural waste generation has predicted for Thailand (0.225 kg/cap/day) followed by Malaysia (0.21 kg/cap/day).

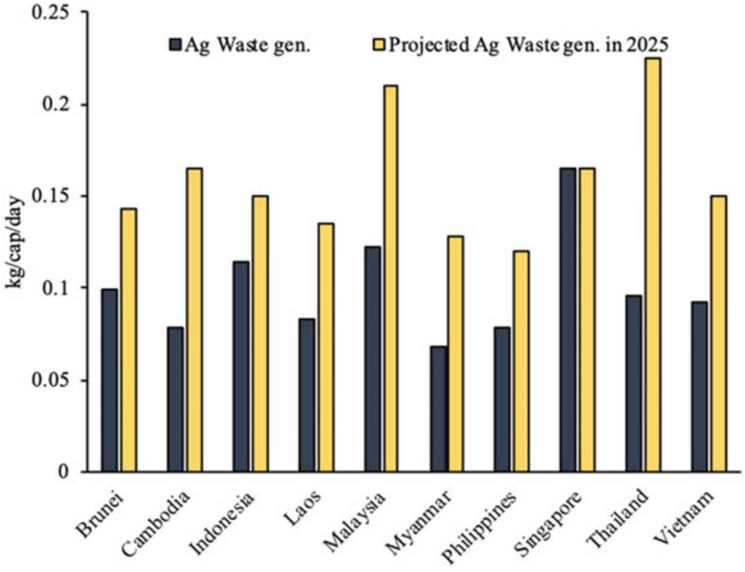

Fig. 21.1 Projection of agricultural waste generated in 2025 in different South Asian countries (Source: Hsing et al. 2004)

21.2.2 Composition of Agricultural Wastes

Agricultural waste composition includes lignocellulose, ultimate, proximate content, and biochemical composition. The moisture content, total carbon, volatile solid, and ash are included in proximate composition and fuel efficacy analysis of the biomass is included in ultimate analysis (Singh et al. 2017). Estimation of lignocellulosic compounds (cellulose, hemicellulose, and lignin) content are included in compositional analysis and biochemical analysis includes the estimation of protein, total carbohydrates, lipids, etc.

The agricultural waste is mainly composed of lignocellulosic compounds (80–85%). The crop residues are composed of cellulose, hemicellulose and lignin at 30–50%, 20–30%, and 7–21%, respectively. The agro-processing waste contains 21–45% cellulose, 15–33% hemicellulose, and 5–24% lignin and the composition of agro wastes vary depending on the different source of origin. As for example, the lignin content of rice bran is less (5%) and sugarcane bagasse contains higher quantity of lignin (20%). Another important component is carbohydrate which varies from 40–85% of the total solid (TS) in agro waste from industrial units and similarly in livestock wastes it varies from 50–60% (Moller et al. 2004). Likewise, composition of other compounds is presented in Table 21.1.

21.2.3 Impact of Agriculture Wastes on the Quality of Air, Soil, Ground Water and Emission of Greenhouse Gases

The elements that are mostly responsible for environmental impacts are carbon(C), nitrogen (N), and phosphorus (P). These elements are widely present in the agricultural wastes of organic origin and are responsible for aggravating global warming and causing adverse effects on soil quality. They are potential of causing eutrophication, soil acidification, salinization, damage to human and animal welfare. Food wastes and manures also release CH_4 in to the atmosphere adding to the greenhouse effect. However, the processing of such wastes is energy-consuming and if urine, animal wastes, slaughterhouse remains are heavy metal contaminated, then the end products will still pose a risk to the environment.

Agriculture is responsible for direct emissions into the atmosphere from various processes in production of raw materials. It can also be accounted for air pollution from other related activities like incomplete combustion of fuels and residues or resuspended soil and other particles preexisting from surfaces due to cultivation, animal movement or material transfer. Burning of agricultural residue in open air produce particulate matter of small size (range < 1 μm) (Amann et al. 2017). Another instance of pollution by agricultural activities is ammonia emission which reacts with sulphur dioxide (SO_2) and nitrogen oxides (NOx) in the atmosphere that is emitted from energy consumption and other industrial processes. A study in Europe have shown the models have consistently yielded the outcome that secondary inorganic aerosols like ammonium nitrate (NH_4NO_3) or ammonium sulphate [$(NH_4)_2$ SO_4] is regulated by the availability of ammonia (NH_3), not only in urban

Table 21.1 Composition of agricultural biomass wastes (Source: Pattanaik et al. 2019)

	Lignocellulosic content (wt. %)			Biochemical Composition (wt. %)		
Feed stocks	Cellulose	Hemicellulose	Lignin	Carbohydrates	Proteins	Lipids
Crop residue						
Paddy straw	30.3–52.3	19.8–31.6	7.2–12.8	–	–	5.9
Wheat straw	32.9–44.5	33.2–37.8	8.5–22.3	–	3.48	5.34
Maize Stover	31.3–49.4	21.1–26.2	3.1–8.8	7.9	3.6–8.7	0.7–1.3
Barley straw	29.2–48.6	35.8–29.7	6.7–21.7	–	3.62	1.91
Agro industrial wastes						
Sugar cane bagasse	43.6–45.8	31.3–33.5	18.1–22.9	–	–	–
Rice bran	39	31	4	23.58	14.6–15.4	16.1–23.8
Coffee husk	24.5–43	7–29.7	9–23.7	58–85	8–11	0.5–3
Jatropha	56.31	17.47	23.91	–	–	–
Oil palm empty fruit bunch	23.7–63	21.6–33	29.2–36.6	–	–	–
Apple pomace	21.22	14.75	18.50	55.86	–	–
Olive deoiled cake	22.0	18.2	50.0	–	–	–
Livestock						
Cattle manure	32.7	24.5	42.8	62.46	15.09	6.85
Pig manure	–	–	–	52.08	23.9	14.3

areas (Petetin et al. 2016; Lackner et al. 2014) but also in rural situations (Beauchamp et al. 2013; Theloke and Li 2013). Agriculture sector is responsible for a significant part of emissions that can adversely affect the human health and balance of the ecosystems (Amann et al. 2017). The emissions mainly generated due to the agricultural activity and wastes are:

- Ammonia (NH_3) from livestock, chemical fertilizers, and manures.
- Particulate matter (PM2.5) (<2.5 μm) from the burning of crop residues, agricultural machineries, movements of livestock during soil cultivation.
- Nitrogen oxides (NOx), from the fertilizers, machineries, and heating.
- Volatile organic compounds (VOC) from crop and animal and also from manure, burning of residue, and use of machinery.
- CH_4 from ruminants, rice production, manure application, and residue burning.
- Nitrous oxides (N_2O) from agricultural soils (microbes) and manure.
- CO_2 from fuel combustion and building up of soil carbon from cultivation and land use change.

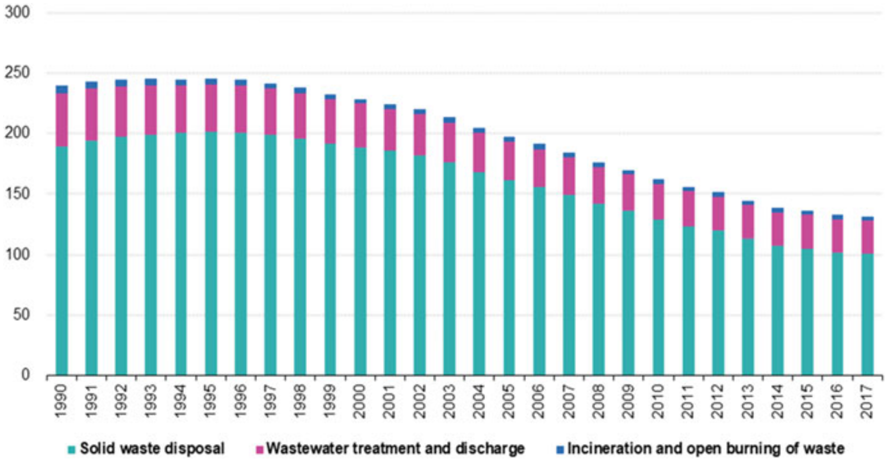

Fig. 21.2 GHGs Emissions of Waste Management from 1990–2017 (Mt of CO_2 equivalent) Source: EEA, republished by Eurostat (online data code: env_air_gge)

The impacts on human health, crop and climate change because of the emissions are enormous. A relevant step in growing of any crop is to remove the crop residues managing the weeds and pests and at the same time preparing the field for sowing in the new season. Burning of residue is generally followed by the farmers as it is a reasonable way to get rid of residues that otherwise is a labor-intensive and time-consuming process (EEA 2016). But, along with release of greenhouse gases, burning also depletes the carbon that is essential to maintain quality of the soil (Lal 2007).

The global greenhouse gas emission by gas as revealed in Fifth Assessment Report by IPCC 2014 indicate that a large amount of CO_2 is emitted by industrial processes followed by forestry and landuse. Organic manure or slurries that are byproducts of livestock production units play major role in release of GHGs including NH_3, methane (CH_4), and N_2O.

Ammonia that are emitted from agriculture related activities are mainly due to breakdown and volatilization from the urea, from manures and slurries (Defra 2002) and can be problematic especially for the surrounding population when large quantities are emanated from concentrated areas like piggery, poultry, and dairy units. Figure 21.2 represents the greenhouse gas emitted due to agricultural waste disposal by different methods. When ammonia enters the atmosphere, it is not only deposited in gaseous form, it also reacts with other gases and forms a multitude of ammonium compounds and gets solubilized in rain drops as it is highly soluble by nature (Defra 2002). On one hand, excess nitrogen can be beneficial to plant species which can exploit the nutrient and on the other detrimental to those which are sensitive to overdose of nitrogen (Defra 2002). Storing and breakdown of manures and slurries, enteric fermentation are the reasons for methane and nitrous oxide emissions. They have global warming potential of 28 and 265 time, respectively, that of carbon dioxide (IPCC 2014). Therefore, these are the major portion of the contributors for extremes of temperature and precipitation.

Without careful handling, the manures, slurries, and inorganic fertilizers get discharged into surface water and infiltrates the soil to reach the groundwater and can cause nutrient enrichment. This may often result in increase of ammonium concentrated in water bodies, which gets converted into nitrate through nitrification with microbial assistance. Nitrate compounds are extremely water soluble and can readily be taken up by growing plants and possess the risk of leaching in to the groundwater especially when it is over-applied to the crop fields in wet conditions. Sometimes, the increase of ammonia concentration may lead to acidification of land and water. The fecal remnants in soil as well as water bodies can also cause heavy metal pollution. Growth stage of the plant is also a prime factor, the amount applied is also related with the stage in which plant can take up the nutrient in optimum amount (Green 2019). Nitrogen can also be associated with potential health hazards as it causes methemoglobinemia (blue baby syndrome) and gastric ulcers (Green 2019). Most of the concentrated organic manures like bone meal as well as inorganic phosphorus fertilizers can also have negative impacts on ecosystems. They generally enter the water as fine sediments that are eroded. As phosphorus is less soluble it is bound to these sediments and remains suspended. They can create imbalance in aquatic ecosystems by algal bloom as they cut off the oxygen that reach to the surface water with the sudden rise of algal growth. Therefore, this condition increases the biological oxygen demand resulting in eutrophication.

21.3 Wastes Recycling and Utilization Options

21.3.1 Waste Management Concepts

The quantity of waste generated in agriculture and allied sector and its potential value in conserving the soil and environment quality clearly point out that there should be proper waste management systems for every farm activity to check the loss, protect the environment, and generate economic benefits to sustain the overall agricultural development. This has become a major issue for the policy makers worldwide (Hai and Tuyet 2010). The residue generated from the agriculture and allied activities in an unmanaged system is generally left in the environment with or without any treatment. This result in addition of unwanted or sometimes hazardous material to the system lead to the degradation of the quality of air, water, and soil. In order to avoid the contamination, this requires proper planning, initiative to use modern technology and definitive guideline to develop agriculture waste management (Obi et al. 2016).

In general, the waste management concept has the following goals (Kan 2009):

1. Shrinking the total quantity of waste through reduce and recycle process.
2. The appropriate groups of refuse should be reintroduced into production cycles as secondary raw material or energy carrier.

3. The biological waste needs to be recycled into natural system.
4. The waste disposed into "landfills" should be recycled in the best possible processes to efficiently reduce the amount of the refuse generation.
5. System must be included with the latest developments/technologies for waste management.

21.3.2 Waste Management Systems

According to USDA field book, agricultural waste management system (AWMS) is referred as "a planned system installed with all necessary components to regulate the byproducts of agriculture in a way that sustains and improves the ecosystem quality (soil, air, water, plant, animal and energy resources)." Therefore, any management system developed in a way that it caters to the requirement of the farmers throughout the year around involving the total aspects of the waste utilization in a sustainable manner.

The AWMS consists of activities which is distinctly described as specific functions (USDA field handbook 2011) and under the broader components there are also other interrelated steps presented in Table 21.2. The purpose of this system is to manage the waste in such way that it is removed, treated, and disposed or recycled in to cleaner and safe material for purposeful use. The proper management of the waste generated through the different agricultural and allied activities is dependent on the consistencies of the feed stock material. In general, the agricultural waste exists in different consistencies and forms (solid, semi solid, liquid, and slurry) require multifarious management techniques and the handling equipment. Therefore, efficient utilization of the waste enhances the resource efficiency which safe guards

Table 21.2 Basic functions of the agriculture waste management system (AWMS) (Source: USDA Field Handbook 2011)

Basic functions	Components/ Sub-parts
Production	Waste sources, kind, consistency, volume estimate, rate and timing
Collection	Method of collection, collection point identification, necessary equipment, structural facilities and management
Transfer	From the point of collection to the storage facility, treatment facility, within the treatment facility and to the utilization site
Storage	Storage time/period, volume, location, facility installation and maintenance and management
Treatment	Physical reprocessing- shredding, sorting, compacting; Thermal reprocessing – Incineration, gasification; Biological reprocessing – Anaerobic digestion, aerobic composting
Utilization	Land application – Distribution system, compatible equipment, application volume and rate; Recycling – Value of recycled products, installation and management of utilization process

the natural ecosystem and benefit the mankind by improving the economic prosperity (Angamuthu 2016).

21.3.3 The "3R" Approach in Agriculture Waste Management

The Sustainable development strategies adopted by the member states of United Nations (UN) in 2015 formulated 17 goals for tackling the poverty, minimize inequality, schemes to spur economic development and improve health and education keeping in mind climate change and preservation of existing natural resources. Among the goals one of the important aspects was advanced waste management systems. Waste management efficiency is better achieved by applying the "3Rs" concept (Bharadwaj et al. 2019). This concept is primarily based on three principles—Reduce, Reuse, and Recycle.

Utmost care should be taken in preparation of agricultural raw materials to minimize the quantity of waste. Some of the materials or its parts thus generated could be reused with slight or no processing for other useful purposes. The residues from the harvest of the crops could be reused by direct application as a nutrient source for the ensuing crops (Hai and Tuyet 2010). The reuse of the wastes saves the resources and reduces the generation of the waste again. The recycling is a complex process where the waste is used in different ways as raw materials to generate diverse products and energy which adds value to the waste and reduces its ill impact on the environment. The "3Rs" approach of waste disposal follows a hierarchy which categorize the impact of the management strategies into six levels (Fig. 21.3) from low to high. The aim of this hierarchy is to efficiently use the waste and minimizes the losses from the waste.

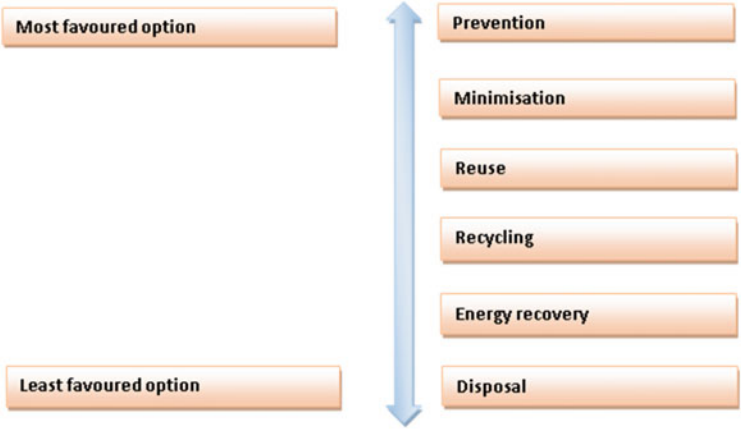

Fig. 21.3 "3R" waste management hierarchy (Source: Demirbas 2011)

21.3.4 Agriculture Waste Utilization Processes

The utilization process involves reuse of the waste, systematic storage and recycling of the waste into usable products (Komnitas and Zaharaki 2012). Selection of any waste management processes must ensure minimum environmental impact and maximum benefit in terms of utilization of wastes. The process of generation of the waste influences the physical and chemical constituent of the agricultural wastes (Obi et al. 2016). The diverse types of waste and their chemical composition determine the type of management strategies and processes adopted for better utilization (Thomson 1991). Agricultural wastes are of organic in nature and these solid wastes are rich source of nutrients. Therefore, different treatment options are used for safe disposal and utilization of these products.

21.3.4.1 Composting

"Composting" is one of the conventional methods commonly used to decrease the amount of waste and transform it into usable products. This transformation is carried out by the microorganisms which reduces the toxicity of the wastes. This process is carried out by mesophilic and thermophilic microbes which results in production of CO_2, water, minerals, and well-decomposed organic matter (Eq. 21.1) (Huang et al. 2006). Compost feedstock is a heterogenous agricultural waste and a residue of varying consistency depending on the sources of the waste generation. The chemical composition of the compost feedstock ranges from simple starches and sugar compounds to highly resistant lignin and cellulose components (Mohee 2002).

$$\text{Organic matter} + O_2 \longrightarrow \text{Compost} + CO_2 + H_2O + \text{Heat}$$

The process of composting has different stages viz. (a) Latent; (b) Growth; (c) Thermophilic; and (d) Maturation stage (Saludes et al. 2008). In the first phase, i.e., the latent phase, the microbial growth proliferates gradually and they get acclimatize to the substrates. In the growth phase, there is rapid increase in microbial population which also raises temperature of the decomposing substrate due to increased activity of mesophilic organisms. This is further increased to very high temperature reaching the peak in thermophilic stage. This high temperature kills the pathogens in the waste substrate and slowly the decomposing mass stabilizes (Turner 2002). Mostly, bacteria are more prevalent in this stage due to the extreme temperature and humidity along with the pH of the decomposing substrates. The temperature cools down and the stable compost is finally available in the maturation stage. Actinomycetes play the major role during this phase decomposing the complex carbohydrates resulting in humus formation. Nitrification and humification are the dominant reactions of this phase and the moisture along with the volatile compounds decreases which indicate the end of the process (Loehr 2012). The composting rate depends on number of factors which include (a) carbon is to nitrogen balance—optimum 25–30:1 along with the other nutrients (b) Particle size—12–50 mm is reported to be optimum but also depends on aeration rate followed by different processes (Biddlestone and Gray 1985) (c) Moisture level—Optimum moisture of 50–70% controls the temperature and influences the oxygenation rate of the composting material (Tiquia et al. 1996). These variables are rate-limiting and at the different steps of decomposition these variables influence the characteristics of the compost which must contain at least 1% nitrogen (N) and phosphorus (P) and potassium (K) not to be less than 1.5%. It should also supply the other nutrients that may range from 0.01% to 0.05%. This process of remediation of agricultural waste produces compost which are ecofriendly fertilizers applied to soils for the enhancement of their quality and productivity (Bernal et al. 2009).

21.3.4.2 Bio-Fuels Production

Different wastes are being recycled to produce "bio fuels" to replace fossil fuels in order to reduce the carbon footprint from the combustion of fuels as an energy source (Naik et al. 2010). There are different categories of bio-fuels (Table 21.3). The agricultural waste is basically lignocellulosic in composition which are being used to produce biogas, bioethanol, biohydrogen, and biodiesel.

Anaerobic Decomposition (AD)

This is another process of treating agricultural waste and recycling is done to produce "Bio gas" using the microbes especially the bacteria. The "Bio gas" is a methane-generated gas through this process can be used in place of LPG gas. The AD process is divided into four stages (Fig. 21.4); the first stage is hydrolysis when bacteria decompose the organic wastes (agricultural) composed of polymers into monomers. The next stage is acidogenesis where the monomers are converted into the organic acids. The third stage is acetogenesis where these acids are metabolized to acetate (CH_3COO-), hydrogen (H), and carbon dioxide (Khan & Faisal 2020).

During this metabolic process, the hydrogen concentration is at low levels due to the hydrogen-consuming bacteria (methanogens) and this stage is the key to this AD process (Tatara et al. 2008) which finally produces methane by the process of methanogenesis. This is carried out by the methylotrophs, hydrogenotrophs, and the acetotrophic bacteria (Ziganshin et al. 2013). This process takes 3–4 weeks depending on the environment and some of the factors like amount and type of waste, pH, moisture, temperature, and the composition of the bacterial flora. This process is very sensitive to the temperature changes and maintenance of the optimum temperature controls the efficiency of the process. The AD process though costly but produces gas which contains 50–70% CH_4; 25–45% CO_2; >5% N_2 and H_2 and traces of H_2S (Merlin and Boileau 2013). The composition of the feed stock for this process is very important and influences the bio-gas yield and its composition. The

Table 21.3 Categories of Biofuels (Source: Rodionova et al. 2017)

Biofuels			
Primary	Secondary		
	1st generation	2nd generation	3rd generation
Fire wood, wood chips, animal waste, crop residues	Biofuels produced from food crops such as corn, sugarcane, soyabean, potato and rapeseed.	Biofuels produced from lignocellulosic biomass (LCB) and its wastes and nonedible plant parts.	Biofuels produced from microalgae and microbes.

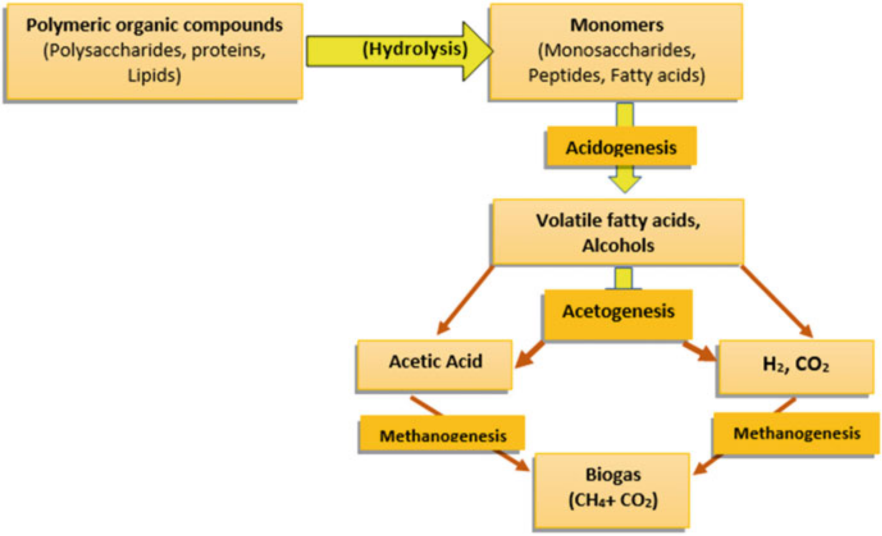

Fig. 21.4 A schematic presentation of AD process for Agricultural waste (Source: Adapted from Khan and Faisal 2020)

Table 21.4 Potential of different Agricultural feedstocks to produce methane (Source: Tamburini et al. 2020)

Agriculture waste	Biomethane gross production – million Nm^3/yr)
Vegetable, fruit and legume waste	0.556
Straws, cobs, stalks	5.334
Cow manure	59.648
Poultry manure	2.438
Oil press residues	0.179
Slaughterhouse waste	2.530
Total livestock residues	125.005
Total Agri-food waste	14.556
Total agricultural residues	6.259

vegetable, fruit, and legume waste of food crops and crop residues such as straws, cobs, stalks are mainly composed of lignocellulosic compounds and livestock manures are the potential source for AD process resulting in production of methane gas (Table 21.4). Totally around 125 million Nm^3/yr. of biomethane is produced per year as compared to crop residues (6.25 million Nm^3/yr) and agri-food wastes (14.5 million Nm^3/yr) (Tamburini et al. 2020).

Bioethanol

"Bioethanol" is an alternative source of fuel which has two chief benefits over the fossil fuels—(1) high octane number and (2) high oxygen content resulting in 80% less emission of CO_2 (Krylova et al. 2008). It is alternative to the toxic methyl tertiary butyl ether for blending with petrol (Yao et al. 2009). Hence, this is an available alternative to the proper utilization of the various agricultural wastes (Table 21.5) which could be supplied as a source of feedstock (Yousuf, 2012) Biofuels- Bioethanol production, etc. These agricultural wastes are composed of lignocellulosic compounds containing cellulose, hemicellulose, and lignin (35–55%, 20–40%, and 10–25%, respectively) (Ghosh and Ghose 2003). For production of bioethanol from the agro-wastes, three processes are followed such as pretreatment, enzyme hydrolysis, and fermentation. The pretreatment is the mandatory process for the production of the bioethanol (biofuels). This process helps in decreasing the crystallinity of lignocellulosic compounds which consist of cellulose, hemicellulose, and lignin and increasing the surface area.

The process delignify the biomass, then hemicellulose decomposition and increasing the biomass porosity (Sarkar et al. 2012), as result of this accessibility to the hydrolysis increases. The pretreatment methods are four namely, physical, physiochemical, chemical, and biological (Fig. 21.5).

After pretreatment, the LCB are converted to monomeric forms by the process of hydrolysis which can be performed either through acid or enzymes. Enzymatic hydrolysis (Saccharification) in comparison to acid hydrolysis require less energy and mild environmental condition resulting in less toxicity, low cost, and lesser corrosiveness (Taherzadeh and Karimi 2007; Sun and Cheng 2002). The enzymes which are majorly used in hydrolysis of LCB are cellulases, hemicellulases, and lignanases which are highly substrate specific. In the fermentation process, several microorganisms are used to convert hydrolysed biomass into several valued products. Industrial use of process for bioethanol production is hampered by suitable

Table 21.5 Different types of AW as a source of feedstock for biofuel production (Source: Yousuf 2012)

Food crops	Non-food/ energy crops	Forest residues	Industrial process residues
-Rice straw	-Giant reed	-Tree residues (twigs, leaves, bark and roots)	-Rice husk
-Wheat straw	-Salix		-Rice bran
-Sugarcane tops	-Jute stalks		-Sugarcane bagasse
-Maize stalks	-Willow	-Wood processing residues (sawmill off cuts and sawdust)	-Coconut shells
-Groundnut stalks	-Poplar		-Maize cob
-Corn straw	-Eucalyptus		-Maize husk
-Soybean residue	-Miscanthus	-Recycled wood (that derived from demolition of buildings, pallets and packing crates)	-Groundnut husk
-Residues from vegetables	-Reed canary grass		
-Residues from pulses	-Hemp		

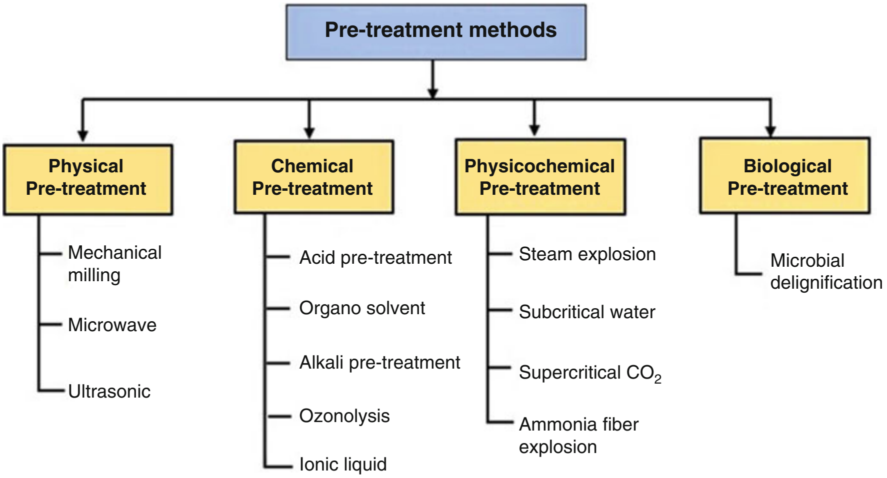

Fig. 21.5 Processes of pre-treatment of lignocellulosic biomass (Source: Pattanaik et al. 2019)

microorganisms (Talebnia et al. 2010). Generally, saccharification stage is integrated with fermentation stage in different approaches like simultaneous saccharification and fermentation (SSF); separate or sequential hydrolysis and fermentation (SHF); simultaneous saccharification and confrontation (SSCF) and consolidating bioprocessing (CBP) (Cardona et al. 2010).

The process mentioned above is being employed under different conditions with limitations. Genetically modified microorganisms are used in fermentation to obtain higher yields and wide substrate utilization rates. The potential to produce ethanol from agriculture waste is tremendous (Fig. 21.6). Different fruit wastes have also been assessed for bioethanol potential which includes apple pomace (38%), banana peel (7.45%), and pineapple peel (8.34%) (Gupta and Verma 2015).

Biohydrogen

“Biohydrogen” fuel is a potential alternate route for utilizing the agriculture waste and is a source of clean energy. Recently, bio-hydrogen has gained attention as a future source of energy (Buitron et al. 2017). Different processes like photo biological, dark fermentation, thermochemical, and enzymatic routes have the potential to generate hydrogen from biological wastes. Among the technologies dark fermentation have been reported to be efficient (Ghimire et al. 2015). Bio hydrogen production by dark fermentation using LCB require pretreatment by physical and chemical methods to enhance the efficiency of the feed stock. Other than the pretreatment, specifically for dark fermentation, factors like pH of the medium and the presence of metal cofactor are important (Chong et al. 2009) as it produces different biofuels along with bio hydrogen.

Fig. 21.6 Second-Generation Bioethanol production from different agriculture wastes. (Source: Gupta and Verma 2015)

21.3.4.3 Pyrolysis

In this method, agricultural bio waste is heated at 400–600 °C temperature in absence of oxygen (Obi et al. 2016). This process is of two basic types—Conventional which generates end products such as acetic acid, charcoal, methanol, and fast/ flash pyrolysis in which the 50–75% feedstocks is converted to pyrolytic acid and remaining portion becomes char or "Bio char". This process of waste degradation produces bio-oil (Yanik et al. 2007) which due to old technology is not environmentally suitable as the oil is thermally unstable turning into gummy paste like material.

The "Biochar" is the byproduct of the pyrolysis of bio-waste including the different agricultural wastes such as poultry litter, waste wood, manure, plant material, bagasse, etc. The international initiative defines bio char as "a solid material obtained from the carbonization of biomasses". Several factors influence the process and its end products which include particle size and shape, physical properties, composition of feed stock and ash content. The biochar characteristics like elemental content and morphological properties are influenced by the temperature. Similarly, the chemical properties like pH, electrical conductivity (EC) and content of dissolved organic carbon (DOC) are also affected by temperature variations (Brown 2009, Joseph et al. 2009).

Application of biochar results in numerous environmental and ecological benefits of reduction in GHGs and nutrient leaching through several losses; improved water retention and better soil structure; and enhanced crop productivity.

21.3.4.4 Construction Materials

Agricultural products and waste produced from processing may be the potential raw material sources for building materials. This helps to minimize utilization of conventional resources which significantly reduces the negative impact on environment (Claudiu and Cobirzan 2013).

Bricks are mandatory in the construction of industries. The process of brick-making in kilns use water and clay, thus depleting the nonrenewable resources and high pollution arises due to the coal burning resulting in emission of GHGs (Luby et al. 2015). The incorporation of agricultural wastes as a partial reduction in the proportion of clay use, is found to be potential strategy for recycling the wastes and reduce the carbon footprint of the entire process (Kazmi et al. 2016). Agricultural wastes such as sugarcane bagasse ash and rice husk ash (Kazmi et al. 2016); oat and barley husk and middling (Kizinievič et al. 2018); wine less, grape seeds and stalks (Taurino et al. 2019) and fruit bunch and coconut fibers (Deraman et al. 2017) when incorporated with clay increased the porosity, excellent compressive strength, greater moisture absorption, and higher density of the bricks. These bricks utilize up to 10% of the agricultural waste when incorporated @ of 4–5% along with the clay. The use of these materials in brick also improved the thermal properties and the acoustic performance where there was reduction in noise by 10 dB and indoor temperature by 6 °C in comparison to conventional bricks (de Siliva and Perera 2018).

Along with the bricks, concrete (mixture of cement, fine and coarse aggregates) are also used for construction purposes (Prusty et al. 2016). Sugarcane bagasse ash, bamboo leaf ash, and groundnut shells (Maraveas 2020) are being utilized to partially replace different components like cement, fine and coarse aggregates to manufacture the green concretes which are reported to improve properties of concrete as per the prerequisite of the construction guidelines.

Agro-wastes are also beneficial for manufacturing insulation materials for buildings. The widely used waste materials are coconut, wood, hemp, straw and flax, and rarely used materials such as sisal, reed, grass, and pineapple (Liu et al. 2017). The properties of insulation materials could be improved by adding wastes like moss fibres, starch, and cardboard. The thermal properties could be further improved by treating the insulating materials with alkali (NaOH) or linseed oil (Maraveas 2020).

Similar to the above-mentioned construction materials, the agro-wastes are also used to manufacture reinforcement materials, particle boards and bio plastics where incorporation of these wastes improve the quality of materials; also result in bio degradable end products helping in protecting the environment.

21.3.4.5 Dye Adsorption by Agricultural Waste Adsorbent

Different types of dye containing effluents are released from various industries which pollute the water bodies resulting in the decline of the quality of the environment. Its effective treatment is also becoming challenge for all the stack holders. Currently numerous techniques broadly categorized into physical, chemical, and biological processes are used to treat the dye-laden effluents (Garg et al. 2004). Among these methods, adsorption is very effective separation technique for removal of the inorganic/ organic pollutants from liquid phase and it does not produce any harmful leftovers.

The different agricultural waste materials either in their natural form or after some physical and chemical treatments are used as adsorbents for treating the wastewater. These materials are low-cost and environment-friendly available in abundance which could be a potential option for treating the polluted water (Rehman et al. 2012). The agricultural waste materials like olive wastes, pineapple stem, ground hazelnut shells, banana waste, coconut bunch waste, mango seed kernel, lemon peel, sawdust, sugarcane bagasse, coconut husk, coffee husk, rice straw, wheat straw, and many more waste have been successfully employed for treating waste water as adsorbent.

21.3.4.6 Production of Bioactive Compounds

An effective way to reuse the agricultural wastes is the retrieval of compounds such as bioactive and phytochemicals from the biomass, which can be used as food, preparation of cosmetics and also an important role in pharmaceutical industry. Of late, this cheap source of feedstock is recycled by Solid State Fermentation (SSF) processes for production these value-added products, majorly various bioactive phenolic compounds (Robledo et al. 2008).

The common bioactive compounds naturally occur in food and plant products in small quantities namely plant growth factors, food grade pigments, antibiotics, alkaloids, phenolic compounds, and mycotoxins. However, commercially, few pigments and phenolic compounds are gaining much importance. Poly phenols and flavonoids are the bioactive compounds found in higher plants act as antioxidants in human beings and help in protecting from different health problems (Robards et al. 1999). The extraction process of bio active compounds from agro-wastes undergoes step-by-step methods where pre-treatment involving the physical, chemical, and biological processes are followed to obtain maximum bio-active compounds from lignocellulose biomass.

The natural bioactive compounds have diverse structure and functions and the amount present in the agro waste is also variable. The compounds like polyphenols are extractable in larger concentration and others are very low in content (Joana Gil-Chavez et al. 2013). There are several techniques of extraction of bioactive compounds from the different sources of biomass wastes. For agro wastes extraction of bioactive compounds by fermentation has potential to provide good quality extracts. During the fermentation process, microorganisms produce the bioactive compounds as secondary metabolites (Nigam 2009).

The agro-wastes such as straw, bagasse, stover, cobs, and husk of cereals composed of lignocellulosic materials are extracted by the solid-state fermentation using fungi produces numerous phenolic compounds (Mussatto et al. 2007). Similarly, the residues of the different fruits and vegetable especially their peels are used as valuable feedstocks for producing bioactive compounds for the pharmaceutical products (Parashar et al. 2014). The physicochemical properties of the bioactive compounds and the availability of the feedstock decide the process of extraction technologies and strategy.

21.4 Agricultural Wastes Use and its Benefits

21.4.1 Soil Quality Improvement

Soil quality improvement is a major focus to keep up soil health by using agrarian waste materials. Eden et al. (2017) stated that decreasing soil fertility and crop yield is a major global concern that is directly related with low soil organic matter (SOM) content in agriculture lands. This reduction has adverse impacts on soil attributes viz. soil aggregation, structural stability, water holding capacity, bulk density, etc. In-situ use of the biodegradable waste in agriculture is a potential option to improve the nature of soils that have been degraded due to the over exploitation of resources like inorganic fertilizers and other agrochemicals in the past, to ensure food protection for a growing global population. Utilization of these wastes in agriculture, offers the win–win strategy of sustainable soil management and improved environmental quality (Dias et al. 2010).

21.4.1.1 Effect on Soil Physicochemical Properties

The physicochemical properties of soil (such as pH, cation exchange capacity, porosity, particle and bulk density, etc.), along with the environment, are adversely affected by indiscriminate use of chemicals like inorganic fertilizers (Zuo et al. 2018), water, and pesticides.

The organic carbon (OC) content in agriculture soils have tremendous influence in fertility maintenance and sustainability of any cropping system (Blanchet et al. 2016). Basically, the use of organics in farming substantially improve the SOC and other nutrient ions and growth components needed by the plants (Rakesh et al. 2020; Srinivasarao et al. 2020a, b). The use of different agro-wastes in soil have great impact on the soil attributes under different ecologies (Table 21.6). The agro-wastes, which are organic in nature, applied in soil improves water retention capacity; increases soil aggregation and stability of the soil structure due to the increase in both the macro- (<2000 micron) and micro-aggregates (250–50 micron) in comparison to the un-amended soils (Nicolas et al. 2014). Similar improvement in nutrient supplying capacity, water holding capacity, cation exchange capacity, hydraulic conductivity, and total porosity was reported (Eibisch et al. 2015) and due to the utilization of agricultural wastes, soil erosion, and nutrient loss because of leaching (Grey and Henry 1999) and runoff loses are reduced. Application of vermicompost which is one of the routes of utilizing the agro wastes as amendment aids in provision of improved soil properties and fertility (Domínguez and Gómez-Brandón 2013).

The utilization of farming waste is viewed as a more secure method of improving soil quality by determining the potential gain and risk balance associated with compost use under field conditions (Alvarenga et al. 2015). Agriculture waste can be utilized to recover exhausted soils, reestablish soil fertility by C-accumulation, and decrease the utilization of synthetic fertilizers and pesticides which also reduces adverse ecological effects. Agricultural waste preserves and increases soil fertility and productivity through the long-term effects on soil micro-biota in intensive

Table 21.6 Soil physicochemical and biological properties as affected by various organic wastes (Source: Sharma et al. 2019)

Soil properties	Effect
Physicochemical	
pH	Increased and/or decreased
Soil aggregate stability	Increased
Bulk density	Decreased
Water-holding capacity	Increased
Micronutrients (Fe, cu, Mn, Zn, etc.)	Increased
Macronutrients (N, P, K) (total or available)	Increased
Electrical conductance	Increased
Organic carbon	Increased
Organic matter	Increased
Biological	
Microbial biomass C	Increased
Microbial biomass N	Increased
Basal respiration	Increased
Enzyme activities	
(a) Dehydrogenase	Increased
(b) Phosphatase	Increased
(c) Glucosidase	Increased
(d) Urease activity	Increased
(e) Protease	Increased
Microbial population (bacteria, fungi, and actinomycetes)	Increased

farming systems (Pérez et al. 2008). Supplementation of agri-waste into the soil is one of the best agronomic methods for its advantages in the suppression of soil-plant disease (De Corato 2020).

Preserving the fertility and sustainability of agricultural systems, composted organic matter input plays a major role to perform nutritional functions, regulates microbial activity, improves soil structure, gaseous exchange, conservation of moisture, and buffering ability. Many studies have shown that use of compost also enhances the macro and micronutrients concentration in soils. To summarize the effect of utilization of agro waste as soil amendments directly impact the soil by increasing the organic matter stocks (Hemmat et al. 2010) due to which there is improvement in soil structure (Celik et al. 2004) nutrient and water holding capacity (Caravaca et al. 2003) ultimately increases crop yield (Zaccardelli et al. 2013).

21.4.1.2 Effect on Soil Biological Properties

The application of processed agricultural wastes in soil has tremendous impact on biological properties along with the physicochemical properties of the soils. Soil microbial activities positively correlated with the production systems Gunapala and Scow (1998). Usage of different organic wastes such as poultry litter, cattle manure, cotton-gin trash, mixed yard waste, and in farming resulted a strong relationship between soil biota and soil chemical properties (Bullucklii et al. 2002). The compost application influences the both physio-chemical properties and the nutrient cycles of the soil there by affecting the microbial dynamics of the soil (Schloter et al. 2003). The higher population density of Trichoderma sp., thermophilic and enteric microorganisms were seen in soil treated with biodegradable waste in comparison to the soil treated with agricultural composts. A field experiment performed by Poulsen et al. (2013) to assess the fertilizing impact on soil microbial activity due to the application of urban and agrarian waste, revealed that soil fertilized with agricultural wastes have beneficial effects on soil microbial properties, viz. basal CO_2 respiration, enzymatic activity, soil microbial biomass carbon, organic matter dynamics in the soil, etc. Harvest leftovers and farmyard compost additions resulted in increase of the soil microbial population under natural and inorganic manures in a conventional swiss cultivating technique (Blanchet et al. 2016). In the long-term trial of utilizing anaerobically processed bio-solids in calcareous soils improved the soil properties which was directly proportional to the rate of application and their recurrence (Roig et al. 2012). Soil properties like SOM and nitrogen availability, microbial biomass and enzymatic activities, carbon and nutrient dynamics were improved because of application of biodegradable agricultural wastes. The mechanism by which the composted waste enhances the biological properties is due to high-degree stable soil structure which allows better water and nutrient cycling and storage in soils (Carrera et al. 2007). Application of compost which has its own microbial population adds to the existing population in soil magnifying the diversity of the soil biotic composition (Ros et al. 2006). Incorporation of stabilized organic matter in the form of composted manure increases the metabolic rate of organisms as result of which dehydrogenase, fluorescein diacetate hydrolysis (FDA), and catalase activity in soil (Bastida et al. 2008) which are the indicators of improved biological health are also impacted.

21.4.2 Impacts of Agricultural Waste on Crop Productivity

Agriculture wastes positively influence the soil physicochemical properties and microbial population which ultimately results in higher crop productivity (Hernandes et al. 2016). The use of stabilized organic waste as a compost in farming aids in provision of recycling of organic matter and nutrients for plant growth. Compost /vermicompost also has plant growth control properties (IAA, gibberellins, cytokinins, and humic acids) and induce a decrease in soil-present phytopathogens (Atiyeh et al. 2002). Five different bio-degradable waste such as cow dung, coir pith, bio-digested slurry, sugar press mud, and weeds were vermicomposted and applied in rice-legume cropping system showed that due to nutrient content and compost maturity time, a mixture of weeds and the bio-digested slurry was the most appropriate for vermicomposting. Amalgamation of vermicompost, fertilizer N and biofertilizer resulted in 15.9% yield increase of rice over sole application of fertilizer nitrogen (Jeyabal and Kuppuswamy 2001). Similarly, in a field experiment, there was improvement in rice and legume yields to the tune of 12.2 and 19.9%

respectively due to integrated vermicompost application (50% N) and rest 50% N through fertilizer N and bio-fertilizer against sole application of synthetic inorganic fertilizers (100% N). Improved responses of tomato and cucumber with respect to the leaf area, plant height, base, and shoot biomass were observed due to the pig manure vermicompost and food waste vermicompost by Atiyeh et al. (2002). The vermicompost's enhance plant growth-containing substances such as enzymes, hormones, and vitamins that promote plant growth (Doan et al. 2015). Bio char application resulted in yield improvement to the tune of 10% have reported (Liu et al. 2013). Similar 10% addition of bio char increased three times the biomass yield of mustard (Houben et al. 2013). Yield increase and biomass increase is due to the increase in available nutrients in soils. Biochar amendment in soils results in increased nutrient concentration in soils and better uptake efficiency by plants. Huang et al. (2013) observed increased nitrogen efficiency in rice fields due to the biochar applications. In USA, peanut shell biochar application resulted in increased N, P, K, Mg and Ca concentration in soil and also resulted in higher pH of soils (Gaskin et al. 2010).

Again, in situ management of residues through conservation agriculture (CA) is possible and is being practiced in some developed countries. Potential benefits of CA through retention of crop residues in many parts of the globe including Indo-Gangetic plains reported by several researchers (Gathala et al. 2011; Hossen et al. 2018; Jat et al. 2019; Mitra et al. 2018; Islam et al. 2019; Mitra et al. 2020).

21.4.3 Environmental Security

Agro-waste is a valuable resource to generate wealth. Recycling of agricultural waste is a helpful tool to decrease ecological contamination, compost could be used as alternative source of fertilizers which could boost food security and ensure financial gains for the farmers. As a result of the higher financial and ecological advantage, the utilization of natural waste fertilizers offers the extraordinary potential, particularly in developing and poor nations. Despite its usage as a fertilizer in farming, stabilization of organic waste often combines common sustainability goals (Case et al. 2017).

Non-judicious use of chemical fertilizers results in land degradation, eutrophication, nitrogen emissions, reduced productivity of N usage in crops and also emits N_2O into the atmosphere (Pathak et al. 2016) which could be substantially reduced by increased use of composted agriculture wastes. Kotay and Das (2008) reported that bio-hydrogen, a clean energy substitute is produced from crop residue biomass. Bioethanol also produced from crop residues. Use of Bioethanol emits 80% less CO_2 in contrast to petroleum. Subsequently, mixing of bioethanol with petroleum is an ideal choice and which substitutes the poisonous methyl tertiary butyl ether (Yao et al. 2009). Biofuel production from organic sources could help in diminishing ozone-depleting substances from the climate and aiding in keeping up the carbon balance in the climate (Naik et al. 2010). Agricultural waste can successfully function in remediating soil which get polluted with natural impurities, for example, oil-based goods, pesticides, chlorophenols (Chen et al. 2015). This is accomplished by two mechanisms (i) Pollutant adsorption by organic matter and (ii) its degradation by microbes (Puglisi et al. 2007). In contrast to traditional and more expensive physical and chemical methods, addition of compost is highly economic and environmental friendly technique for soil bioremediation. The process of composting and vermicomposting also emits GHG, but they are biogenic in origin and therefore not considered as source of addition to the global GHG emissions (IPCC 2014). Application of biochar along with organic and inorganic fertilizers were found to reduce GHG emission in crops grown in upland situations (Li et al. 2017). Therefore, agricultural waste recycling is one of the potential routes for reducing GHG emissions, C sequestration and is a sustainable alternative way to mitigate the climate change.

21.5 Policies and Programmes to Develop Agricultural Waste Management (AWM)

Agricultural sector generates huge amounts of wastes, which are the great source of plant nutrition as well as a serious threat to the environment and life. Intensive agricultural practices involved chemical pesticides, fertilizers etc., have an increasing impact on the environment and biodiversity.

Unless proper decision and involvement of all the stakeholders, environmental degradation would further accelerate and harmful to the global security. Limited technologies, lack of detailed regulations on AWM for environmental protection, unclear information on responsibility of functional departments under Ministry of Agriculture, no detailed policy addressing advantages, and limited awareness on communities, agencies and enterprises about potential of agricultural wastes and its co-benefits, etc., are further becoming a barrier for policy implementation. However, the overall policy that regulates agricultural waste management today is mitigation of pollution and prevention of environmental degradation from all types of wastes. Yet, the major goal of current policy system on waste management is to recycle the organic matter which is the rich source of plant nutrients back to the soil system and reduce the stream of organic waste going to landfills (Al Seadi and Holm-Neilson 2004). Along with socioeconomic status, it is a need of the hour to present the diversified strategy of agricultural waste resources in order to develop eco-agriculture and cyc-economy (Liu et al. 2013). However, the status must depend on technical provisions, investment priorities and the policy guidance to promote agricultural waste resources.

21.5.1 Central Schemes and Policies

Crop residue burning is one of the major issues in India which is becoming the significant cause for global warming and climate change. However, the government has put full stop to this by implementing some Acts which are in operation viz., The

Environment Protection Act, 1986; The Sect. 144 of the Civil Procedure Code (CPC) to ban burning of paddy; The National Tribunal Act 1995; The Air Prevention and Control of Pollution Act 1981 and The National Environment.

Appellate Authority Act, 1997. Predominantly, in the states of Haryana and Punjab, Uttar Pradesh, Rajasthan, stringent measures have been taken by the National Green Tribunal (NGT) to limit the crop residue burning (Lohan et al. 2018; Kumar et al. 2015). The Rashtriya Krishi Vikas Yogna (RKVY) was launched by the govt. of India in August 2007 under State Plan Scheme of Additional Central Assistance (Singh and Prabha 2017). This scheme is to demonstrate and train the farmers about the bio-waste management. In the eastern Uttar Pradesh, eight demonstration and training projects on agro-waste bio-conversion and bio-compost production was established to train around 456 farmers. This has supported the farmers in gaining economic advantages (Singh and Prabha 2017). The National Policy for Management of Crop Residue (NPMCR) recently developed by the Ministry of Agriculture of India with the major objectives viz., promoting the technologies related to in situ crop residue management and optimum utilization; promote and develop appropriate farm machineries, remote sensing based technologies for crop residue management under the monitoring of Central Pollution Control Board (CPCB) and National Remote Sensing Agency (NRSA) (NPMCR 2014). The National Thermal Power Corporation (NTPC) implemented by the govt. of India raised the importance of crop residues in electricity generation; recently directed to utilize the crop residue pellets (about 10%) to mix with coal to generate the power (The Hindu Crop Residue-Coal Mix to Nix Stubble Burning. 2018). This policy has benefitted the farmers and allowed to sell the leftout crop residues in the field with a financial return of around Rs. 5500 per ton of residue. Such profitable solution to the farmers are yet to be in action. Various policy options for agricultural waste management (AWM) presented in Fig. 21.7.

21.5.2 Policy Proposals for the Improvement of Agricultural Waste Management

21.5.2.1 Legal Document and Management System.

To effectively manage the agricultural wastes, legal system is essentially important. However, its effect on individuals and organizations related to their behavior will be at limited degree. Therefore, it is critical to have obligatory regulations on infrastructure development viz., centralized wastewater treatment systems and relevant sewage systems to monitor and report on wastewater and solid waste treatment activities regularly. In addition, specifically for the agricultural sector, it is vital to create central coordinated system of environmental management with an organization and a system as per the international standards in general, in order to ensure a good, human-friendly environment.

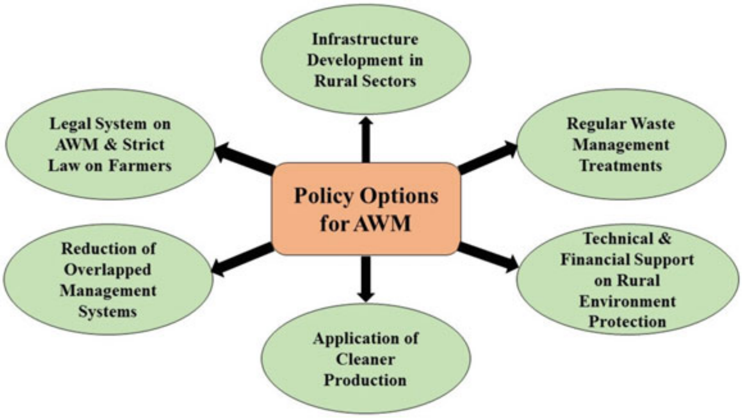

Fig. 21.7 Policy options for agricultural waste management (AWM)

21.5.2.2 Building Strategies and Development Plans

Attention is required on agricultural waste management and planning in every agricultural production sectors viz., centralized breeding farms and intensive cultivation areas. In case of biogas generation in the countries like India and China, use of biogas has developed efficiently both in quantitative and qualitative manner after establishing governmental biogas organizations.

21.5.2.3 Infrastructure Investment

Majority of the farming sectors are suffering from financial crisis and technical support. Policies are crucial to develop the monetary support and technical assistance in order to regulate and address the rural environment pollution and particularly the agricultural waste management. Besides the infrastructure development in rural areas, treatment mechanisms/systems should be invested by the agricultural cooperatives for wastes generated through breeding and cultivation. This would raise awareness on environmental protection among the participants and the community particularly from the agricultural background.

21.5.2.4 Development of Renewable Energy

It plays a significant role in benefitting the environment and balancing energy supply and demand. Many countries across the world and its governments have adopted the policies to upgrade and hasten the energy utilization technologies from the rural biomass that brings changes in traditional systems of inefficient management. Inputs from the research and development (R&D) technologies related to energy utilization and management of agricultural waste should be further increased, support and publicity for large-scale utilization of farm wastes is need to be improved, legal and policy systems are much necessary to utilize AW and its byproducts, livestock, and slaughterhouse waste resources must be reasonably estimated, initialization to participate in agricultural waste utilization and energy production should be executed for every society.

21.6 Conclusion

Recycling of agricultural waste is emerging as a potential option to ensure the environmental stability and nutritional security of livelihood. However, despite the potential values and benefits of agricultural wastes, limited awareness with lack of concern for managing wastes in agricultural sector has become a major constraint in reducing environmental hazards as influenced by waste materials. The farmers mostly do not care about the legal aspects of environmental protection which makes it very difficult to implement. At the same time there is no such strict monitoring system through which we can sort out the problem. The only way to protect the environment from these types of pollution is to convert the residues into usable form such as biochar, composting, in situ management of crop residues through conservation agriculture, etc., but its effective implementation at grass root level is indeed a challenging task to the present generation. Further, the problem is more socioeconomic rather than agricultural or waste management options. A number of technologies have been addressed in this chapter to transform the current agricultural system into a sustainable practice, but unless proper decision and involvement of all stakeholders, environmental degradation would further accelerate with its detrimental impacts on global security. Thus, we are in strong opinion that to protect environment with saving of resources and to build a shared vision on environmental protection, involvement of government is much critical to impose proper policies to recycle and utilize the agricultural waste.

21.7 Way Forward

- Creating awareness on the importance of agriculture wastes and its utilization which is crucial.
- Inputs and support to research and development (R&D) in the energy utilization technologies for AW management should be further enhanced.
- Legal policy systems should be implemented to utilize the byproducts of agriculture and agricultural wastes.
- Support should be given to improve the large-scale energy utilization in agriculture wastes.
- Reasonable estimation of wastes generating from the agriculture and its allied sectors is important.
- A coordination system is required to create a linkage between people's growing material and cultural needs for the sustainable management of the available resources.

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Ethanol Production from Sugarcane: An Overview

22

Shiv Prasad, Vikas Chandra Gupta, Rajan Bhatt, and M. S. Dhanya

Abstract

Sugarcane is grown in about 26 million ha globally, mostly in tropical to subtropical zones, including the Indian sub-continent. India is a leading producer and consumer of sugar in the world, with annual 25–32 million tons of production and contributes nearly 15–17% of global sugar production. Its cultivation is an excellent sucrose source, commonly referred to as table sugar or granulated sugar. Molasses, a byproduct of sugar processing, are currently being used for bioenergy production, especially ethanol, because of economically viable resource. During extraction of juice from sugarcane, vast amounts of bagasse are also generated and burned in plant boilers, which are uneconomical and sources of air pollutants. Various physical, chemical, biological pretreatment, and enzymatic hydrolysis/ saccharification and fermentation are applied to produce ethanol from sugarcane bagasse. Scientists are trying to use this bagasse as an economically viable option to produce ethanol and develop inexpensive technologies that practically apply pretreatment, saccharification, and ethanol fermentation at an industrial scale. In

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future, utilization of these innovative bioconversion technologies, especially simultaneous saccharification and fermentation (SSF), will give a new alternative bioeconomy. It would also provide sustainable use of sugarcane bagasse to produce bioethanol to manage environmental and socioeconomic issues, including dependence on nonrenewable fossil fuel resources.

Keywords

Bagasse · Ethanol · Hydrolysis · Molasses · Pretreatment · Sugarcane

Abbreviations

AFEx	Ammonia fiber explosion
AMImCl	1-Allyl-3-methylimidazolium chloride
DAC	Department of Agriculture Cooperation
E10	10%Ethanol blending with petrol
E20	20% ethanol blending with petrol
EBP	Ethanol Blending Program
$FeCl_3$	Ferric Chloride
GAIN	Global Agriculture Information Network
GOI	Government of India
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulfuric acid
Mha	Million hectare
MT	Million tons
NaOH	Sodium hydroxide
NBP	National Policy on Biofuels
NH_4OH	Ammonium hydroxide
NRRL	Northern Regional Research Laboratory (USDA)
OMCs	Oil-marketing companies
SCB	Sugarcane bagasse
SSF	Simultaneous Saccharification and fermentation
tha^{-1}	Tons per hectare^1
USDA	United States Department of Agriculture

22.1 Introduction

Sugarcane crop is a member of the family Gramineae (Poaceae) widely grown and occupies a significant position in the world's agricultural economy, including India. Sugarcane is a prime source of sugar and cultivated either as the main cash crop or commercial-led industrial crop and employed over a million people directly or indirectly. In the world, sugarcane-producing countries occupied between latitude 36.7°N and 31.0°S of equator spreading from tropical to subtropical zones (Shukla et al. 2017). Sugarcane cultivation was started by indigenous people of New Guinea and spread during human migration westwards to maritime Southeast Asia and the Indian sub-continent. Today, most of the commercially cultivated sugarcane are cross-bred with some wild species of sugarcane family. The sugarcanes cultivated dominantly belong to (1) thin and hardy types *Saccharum barberi* and *S. sinense*, and (2) thick and juicy *S. officinarum. S. officinarum* is a noble and highly prized sugarcane with large soft-rinded juice containing stalks and high sugar content, mainly disaccharide (sucrose).

India is a leader in production and consumption of sugar globally, with annual production of 25–32 million tons contributing nearly 15–17% of world's sugar production. In India, 55 varieties are notified in different parts of the country and grown commercially on 4.9 mha of agricultural land, with an average of 69.5 t ha^{-1} productivity (Shukla et al. 2017). Sugarcane is the preferred crop for sugar production and has become an ecofriendly and green energy source. The Government of India has also allowed ethanol production directly from sugarcane juice to avoid surplus sugar production. This permission will pave the way for blending with petrol and saving lots of precious foreign exchange on importing crude oil. For this, the sugar industry will require varieties suitable for higher biomass with more juice recovery.

Making ethanol from sugarcane starts with cane stalks crushing and extracting a sugar-rich cane juice. Cane stalks juice is finally fermented by yeast *Saccharomyces cerevisiae* to generate ethanol (Prasad et al. 2007; Kumar et al. 2018). The utilization of byproduct resources, i.e., molasses, and bagasse, makes sugar distillery industries stable and self-sustained. The development of novel technologies and advances in research is required to ultimately support the agro-based industrial sector's growth with a more profitable, sustainable, and environmentally responsible sugar system. It would also act as a win–win situation for both consumers, who happen to be the main driving force for revenue generation. These innovations would also have no harmful impact on the environment.

22.2 Sugarcane in the World: Significant Countries

Sugarcane is grown in about 26 million ha globally and contributes 75% of total sugar production with 171 million tons (DAC 2020), while the rest is produced from sugar beet. The top 10 sugarcane-producing countries are shown in Table 22.1. Currently, Brazil is the biggest sugar producer in world. India is second-highest sugar producer country after Brazil. As of 2019, India is accounting for 24.5% of the world's sugarcane production. Global sugar production is forecasted for 2020–2021 to 188 MT (raw value) due to higher production in Thailand, India, and Brazil (USDA 2020). The Indian sugar industry is entirely based on the availability of sugarcane. Most sugarcane farmers and many agricultural laborers are involved in the rural population's sugarcane cultivation and ancillary activities. The sugar

Table 22.1 Top 10 major sugarcane producing countries

S. N.	Country	Area (Mha)	% to world	Production (MT)	% to world	Yield (T/ha)	Sugar Production (MT)
1.	Brazil	9.8	37.1	739.3	39.4	75.2	35.8
2.	India	5.1	19.1	341.2	18.2	67.4	27.3
3.	China	1.8	6.9	125.5	6.7	69.0	13.3
4.	Thailand	1.3	4.9	100.1	5.3	75.7	10.2
5.	Pakistan	1.13	4.3	63.8	3.4	56.5	4.7
6.	Mexico	0.78	2.9	61.2	3.3	78.2	6.5
7.	Indonesia	0.45	1.7	33.7	1.8	74.9	2.5
8.	Philippines	0.43	1.6	31.9	1.7	73.2	2.5
9.	Colombia	0.40	1.5	34.9	1.9	85.9	2.3
10.	Argentina	0.37	1.4	23.7	1.3	64.1	2.1
	World	26.5		1877.1		70.8	172.4

Data source: https://sugarcane.dac.gov.in/pdf/StatisticsAPY.pdf

industry also employs about a million workers (skilled/semi-skilled), mostly from rural areas.

22.3 Sugarcane Producing States of India

Sugarcane is India's most important crop grown in distinct agro-climatic regions, viz., tropical and subtropical. The tropical region includes Maharashtra, Gujarat, Madhya Pradesh, Goa, Pondicherry, Tamil Nadu, Andhra Pradesh, Karnataka, and Kerala. The sugarcane subtropical region consists of UP, Bihar, Haryana, and Punjab. India has a unique climate to grow sugarcane throughout the year. Table 22.2 shows state-wise sugarcane production (lakh tons) trends from 2013-14 to 2017-18 in India (DAC 2020). Around 55% of the country's total cane area is in the sub-tropics part. India takes pride in producing 3550.9 lakh tons of sugarcane in 2017–2018.

Uttar Pradesh and Maharashtra are the top two states known for sugarcane crop production. The sugarcane production in Uttar Pradesh for the year 2017–2018 was 1623.4 lakh tons, received the top position in the list of top states in India. In Uttar Pradesh, Meerut, Bareilly, Saharanpur, and Bulandshahr are known districts for cane production. With around 9 lakh hectares of land, Maharashtra produced 726.4 lakh tons, thus securing the second position in state ranks. Karnataka was in the third position with 299.0 lakh tons of sugarcane production and gained massive popularity to make India's top-quality sugarcane**.** Tamil Nadu, Bihar, Gujarat, and Haryana produced 165.6, 165.1, 122.3, and 87.3 lakh tons of sugarcane. Andhra Pradesh has perfect soil for sugarcane production and produced 79.5 lakh tons. Other states also contributed to a fair amount of sugar production in the country (Table 22.2).

Table 22.2 State-wise sugarcane production in India (Lakh tons)

States	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018
Uttar Pradesh	1346.9	1330.6	1453.9	1401.7	1623.4
Maharashtra	769.0	847.0	736.8	522.6	726.4
Karnataka	379.1	437.8	378.3	273.8	299.0
Tamil Nadu	324.5	280.9	254.9	189.9	165.6
Bihar	128.8	140.3	126.5	130.4	165.1
Gujarat	125.5	143.3	111.2	119.5	122.3
Haryana	75.0	71.7	66.9	82.2	87.3
Andhra Pradesh	120.1	99.9	93.5	78.3	79.5
Punjab	66.8	70.4	66.1	71.5	75.3
Uttarakhand	59.4	61.7	58.9	64.8	71.4
Madhya Pradesh	31.7	45.7	52.8	47.3	54.3
Telangana	33.8	33.4	24.1	20.6	22.2
West Bengal	19.5	21.1	20.8	15.5	12.9
Chhattisgarh	0.2	0.5	0.7	8.5	12.5
Assam	10.8	11.0	10.4	12.1	11.2
Jharkhand	4.6	4.7	7.1	5.1	5.2
Rajasthan	3.6	4.1	5.3	4.9	4.0
Orrisa	9.4	7.2	5.8	3.4	3.4
Kerala	2.2	1.5	1.4	1.1	1.2
Others	10.6	10.6	9.3	7.5	8.7
Grand Total	3521.4	3623.3	3484.5	3060.7	3550.9

Data source: https://sugarcane.dac.gov.in/pdf/StatisticsAPY.pdf

22.4 India's Biofuel Policy and Ethanol Blending Program

The Government of India started ethanol blending program to achieve sustainable development goals, energy security, employment, a cleaner and healthier environment, and greenhouse gas emissions reduction with the National Policy on Biofuels (NBP) in 2009. NBP-2009 targeted an ethanol blending of 20% in petrol by 2017. While under Ethanol Blending Program (EBP), the GOI endorsed 10% (E10) mandatory ethanol blending with petrol/gasoline across whole cane-growing states. One motive was that ten million liters of E10 biofuel/ethanol could save Rs. 28 crores in forex and about 20 thousand tons of CO_2 emissions. However, by 2017, GOI had achieved only 2% blending with petrol and about 0.1% with diesel at the national level (Mandal 2020).

The newly introduced India's National Biofuel Policy 2018 asks to accomplish a national average of E20 for gasoline and B5 for diesel by 2030. The new EBP stipulates the ethanol procurement directly produced from molasses, juice, and spoiled food grains such as broken rice and wheat. GOI has also allowed ethanol production straight from sugarcane juice to avoid surplus sugar production. This permission paves the way for its blending with petrol and saves a lot of foreign exchange on importing crude oil. For this, the sugar industry will require varieties suitable for higher biomass. India reached its maximum ethanol market penetration at 5.8%, compared to the previous record of 4.1% last year. It is predicted that all available ethanol, if used exclusively for EBP, would meet a 6.6% blend rate (GAIN report 2020).

22.5 India's Ethanol Production, Supply, and Consumption

India's ethanol production, supply, and consumption are presented in Fig. 22.1. According to the GAIN report, currently, India has almost 330 distilleries, generating over 4.8 billion liters of ethanol per year. Of this total, about 166 distilleries distilled 2.6 billion liters of ethanol used in biofuel and industrial chemicals. The Indian Sugar Mill Association's total quantity offered for EBP was 1.8 billion liters, of which 1.6 billion liters were blended with gasoline to mark a 4.1% blend rate for 2018. India's total ethanol consumption in 2019 was recorded at 3.1 billion liters (Fig. 22.1).

Although domestic production has been risen, India remains a net importer of ethanol. United States is largest ethanol supplier to India. In 2018, Indian ethanol imports were down 14% to 633 million liters, valued at $269 million. Generally, industrial and chemical users in India import ethanol to augment their cumulative demand, mainly when local supply is short. Overall, import demand remains high, around 750 million liters, it was maximum in this decade. A recent USDA report shows that India's average ethanol blend rate was reached approximately 5.8% in the year 2019, which was 4.1% in the previous year 2018 (Fig. 22.1). Sugar mills and oil marketing companies (OMCs) playing an essential role in the ethanol blending program. Some of the states like Uttar Pradesh, Karnataka, Haryana, and Punjab, Uttarakhand and Bihar achieved more than 5.8% ethanol blending levels with petrol (GAIN Report 2020).

22.5.1 Bioethanol Production from Sugarcane Molasses

Sugarcane has one of the main advantages of per hectare higher productivity, and lower ethanol production cost than other crops (Rudorff et al. 2010). Another advantage is repetitive sugarcane harvests from the same land due to its *ratooning* nature and allows two or three cycles of crops before replanting (Rudorff et al. 2010). A schematic diagram of sugarcane ethanol production is shown in Fig. 22.2.

A series of equipped mechanical rollers extract the sucrose-containing juice from sugarcane. The extracted juice is then cleaned using lime, sulfur, and carbonation (Laluce et al. 2016; Kumar and Meena 2020). After that, the juice is concentrated into syrups, reducing energy consumption during the distillation process. A considerable amount of bagasse is also generated during juice extraction, which is generally burnt in boilers to produce heat and power (Dias et al. 2011; Zossi et al. 2012). Concentrated cane juice is mixed with remaining clarified cane juice to make a final

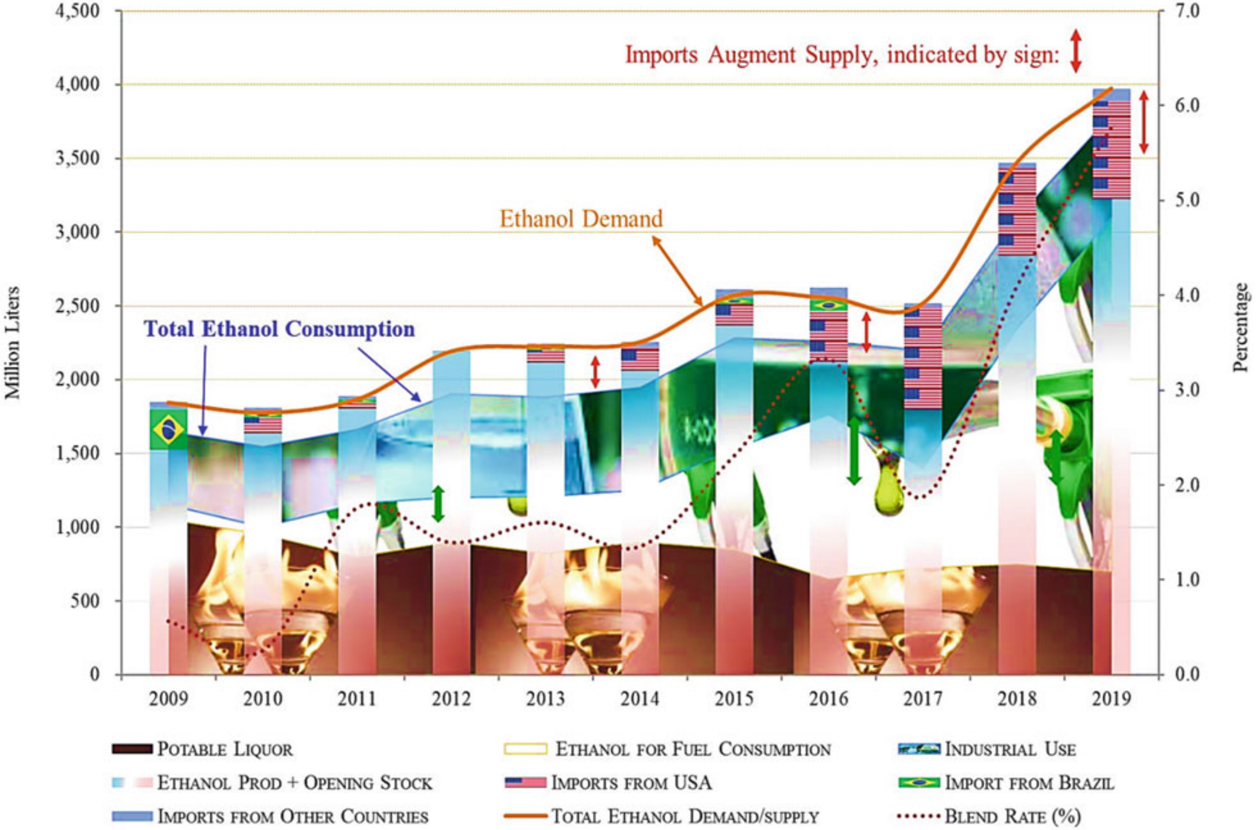

Fig. 22.1 India's ethanol production, supply, and consumption

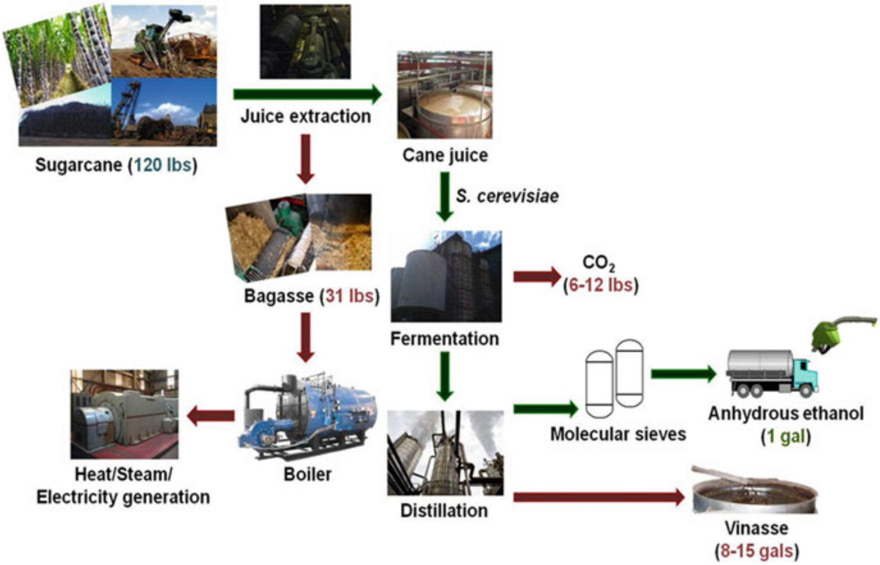

Fig. 22.2 Schematic diagram of sugarcane ethanol production

feed stock containing 22.5% (w/v) and cooled before loading on fermenters (Laluce et al. 2016). Yeasts-like *Saccharomyces cerevisiae*, *Kluyveromyces marxianus,* and bacteria *Zymomonas mobilis* are good microbes used most commonly to ferment molasses and cane juice as substrates (Brandberg et al. 2007; Prasad et al. 2007; Gasmalla et al. 2012; Rudorff et al. 2010; Laluce et al. 2016). After fermentation, the fermented broth is distilled, and after molecular sieving, obtained anhydrous ethanol can be used as fuel-grade ethanol in the vehicle (Gómez-Pastor et al. 2011; Laluce et al. 2016).

Ethanol production from molasses and cane juice is a well-established technology and gets attention due to its usage and applications in the ethanol blending program worldwide. However, there are two key wastes originate from sugarcane juice processing-to-ethanol fermentation (1) bagasse (solid) and (2) vinasse (liquid). Sugarcane bagasse (Fig. 22.3) can have several uses like energy to provide heat/steam/electricity for ethanol and biodegradable paper products.

Vinasse, produced from the distillery, also known as spent wash, is created as an unused waste at bottom of distillation unit column, following ethanol recovery process. Vinasse is characterized as dark-coloured with high organic content and acidic nature, having a very low pH (4.0–4.5). It can be used to produce methane through methanization before disposal. However, currently, treated vinasse disposal is a significant concern for sugarcane industries.

Fig. 22.3 Bagasse from sugar mills and vinasse from the distillery

22.5.2 Bioethanol Production from Sugarcane Bagasse

Approximately 250 kg of bagasse is produced per ton of sugarcane. Surplus sugarcane bagasse, as shown in Fig. 22.2, can also be used to produce ethanol. A detailed description of bioethanol production from sugarcane bagasse is discussed as follows.

22.5.2.1 General Mass Balance and Compositions of Sugarcane Bagasse

Sugarcane biomass is constituted by fiber, juice, or syrup (water), soluble solids, and non-soluble solids (Fig. 22.4). It contains 73–76% water, soluble solids 10–16%, and dry fiber 11–16% (Morandin et al. 2011; Kumar et al. 2021). The fiber fraction is originally found in the cane's stem. The non-soluble solids fraction is not dissolved in water. Soluble solids fraction is readily dissolved in water, primarily composed of sucrose and other chemical constituents (Triana et al. 1990). General mass balance and composition of bagasse of sugarcane are presented in Fig. 22.4.

Sugarcane bagasse comprises cellulose, hemicellulose, and lignin commonly referred to as lignocellulosic biomass (Ahmadi et al. 2016). Cellulose is a polymer of hexose sugar, e.g., glucose. Hemicellulose is also known as a polymeric form of carbohydrate (a pentose sugars, e.g., xylose mainly) and hexose sugars (da Silva et al. 2010; Meena et al. 2020). The lignin content makes lignocellulosic biomass recalcitrant to enzymatic hydrolysis/saccharification and limiting cellulolytic enzymes' accessibility. Therefore, delignification process is required to improve enzymatic hydrolysis conversion rates (Prasad et al. 2007).

The hexose and pentose sugar of biomass could be well utilized for producing bioethanol by a different established metabolic mechanistic system of microbial origin. Given its due consideration, it is quite exciting to looking at the vast amount of waste in terms of bagasse being generated annually. This could ultimately be an energy currency if the suitable conversion technology of such huge waste is in place to tap the entrapped sugar from biomass. Despite an established ethanol fermentation technology, the alternative utilization of sugarcane bagasse is still awaiting to realize its commercial potential due to severe challenges of biomass conversion into ethanol

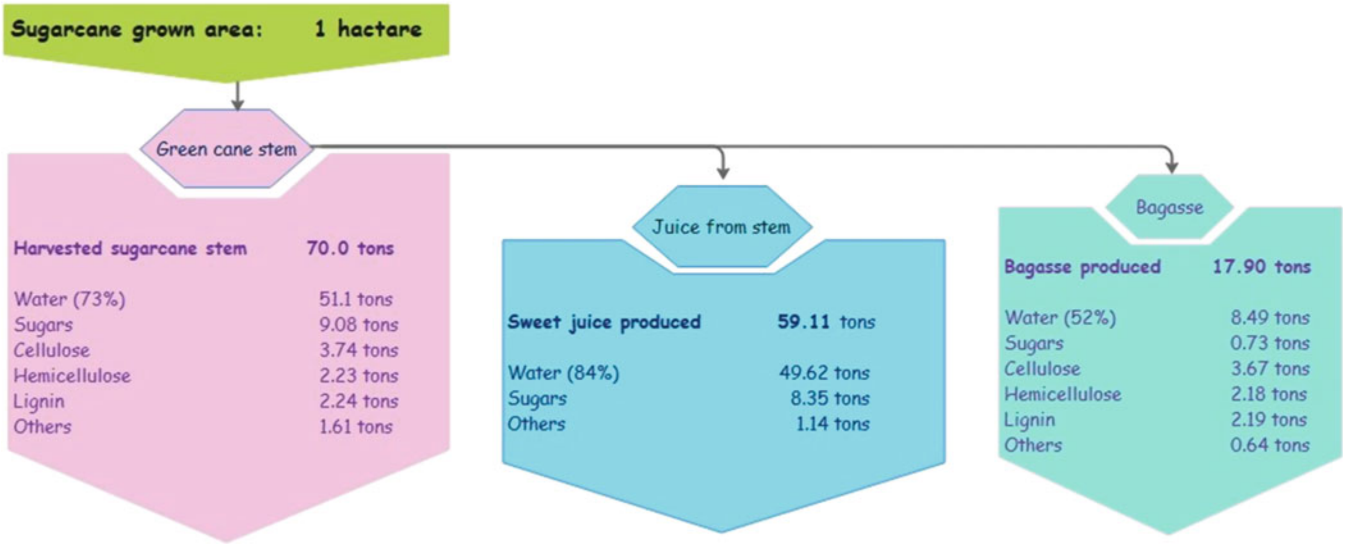

Fig. 22.4 General mass balance and composition of bagasse of sugarcane (*Data source:* Gnansounou and Dauriat 2005)

as an ultimate product. The precursor carbohydrate monomeric sugar molecules required to produce ethanol by the ethanologenic microbial system are freed first and readily available from sugarcane bagasse.

22.5.2.2 Pre-treatment of Sugarcane Bagasse

The pretreatments' chief objective is to breakdown naturally occurring lignin structure and disrupt cellulose crystalline structural fibrils for enhancing enzyme accessibility to cellulose during hydrolysis and saccharification step (Mosier et al. 2005; Prasad et al. 2007; Ahmadi et al., 2016; Silva et al. 2018). Pretreating sugarcane bagasse with numerous alternative methodologies has been applied with an optimal combination of a process variable to release maximum free fermentable hexose and pentose sugar for ethanol fermentation. The primary pretreatment methods employed over a variety of sugarcane bagasse for effective release of fermentable sugar include physical pretreatment, e.g., milling, microwave, pyrolysis (da Silva et al. 2010; Binod et al. 2012; Savou et al. 2019); chemical pretreatment, e.g., acid, alkali, oxidative, ozonolysis, organosolv, wet oxidation (Martín et al. 2007; Zhang et al. 2018; Prasad et al. 2020); combined physico-chemicalpretreatment, e.g., hot water, hydrothermal steam explosion, ammonia fiber explosion, and CO_2 explosion (Silva et al. 2018) and, biological pretreatment using brown rot, white rot, and soft rot fungi, and various bacterial strains (Beeson et al. 2015; da Silva et al. 2010). The selection of appropriate pretreatment methods depends on the biomass type and composition of biomass and pretreatment conditions. The different pretreatment strategies, along with a comprehensive chart of reaction conditions, inhibitors generation, and the overall yield of fermentable sugar with each method's merits and demerits, have been tabulated in Table 22.3.

Physical Pretreatment Methods of Sugarcane Bagasse

Biomass particle size plays a vital role in an efficient and enhanced release of fermentable sugar from sugarcane bagasse due to increased enzyme accessibility to biomass cellulosic content with increased biomass to surface area ratio. Milling is a physical mode of mechanical operation by which sugarcane bagasse particle size is reduced to a level of 0.2–2.0 millimeters, increasing the biomass to surface area for effective enzymatic hydrolysis of biomass for improved yield of fermentable sugar (Tyagi et al. 2019). An enhanced yield of glucan and xylan was reported (68.17 and 54.19%, respectively) using ball milling of sugarcane bagasse for a prolonged milling period from 5 to 20 minutes (Sujan et al. 2018). Though milling mode of physical operation is advantageous due to no generation of inhibitors in the process, associated high energy and operation cost is a significant disadvantage (Canilha et al. 2012; Yadav et al. 2020).

The complex bonding between biomass constituents may be broken down or released by supplying a precise amount of heat within a shorter period of time (Binod et al. 2012). A large amount of heat could be well transferred in less time using the microwave, an excellent alternative to a conventional heating system. The microwave treatment method offers numerous advantages in achieving improved fermentable sugar from sugarcane bagasse, such as uniformity of heat transfer within a

Table 22.3 Examples of various sugarcane bagasse pretreatment strategies to produce fermentable sugar for ethanol production

Pretreatment method	Process variables	Reaction mechanism	Fermentable sugar yield	Inhibitors profile	Advantage	Drawbacks	References
Physical Pretreatment							
Milling	Particle size 0.2-2 mm	Defibrillation effect	Glucose:78.7%, Xylose: 72.1%	NA	Decreasing crystallinity	High energy cost	De Silva et al. (2010)
Microwave	1% NaOH at 600 W for 4 min followed by enzymatic hydrolysis	Electromagnetic radiation cause displacement inside the biomass	Reducing sugar: 0.665 g/g dry biomass.	Least	High Heating in less time	Low radiation penetration in bulk biomass	Binod et al. (2012)
Chemical pretreatment							
Acid / Alkali	0.2 g of bagasse immersed in 8 mL 0.2 M H_2SO_4 or NaOH	Solubilize hemicellulose and lignin in high heat	Higher reducing sugar release in less time	Furan, carboxyl, phenolics	Operate at low/medium temperature, low energy costs	Corrosion and expensive to maintenance	Lee et al. (2011)
Wet oxidation	185 °C, 5 min, and acidic pH	Solubilization of hemicelluloses and lignin	Sugar yield: 16.1 g/100 g	Carboxyl, phenols, furfural at 195 °C	Decrease alkali/acid demand	Oxygen and costliercatalyst	Martin et al. (2007)
Ozonolysis	O_2 flow of 0.5 L/min, bagasse-20gram at 40 °C for 30 min	Delignification with slight hemicellulose degradation	Glucose: 89.7%	Does not produce toxic residues	Effectively removes lignin content	High cost of ozone	De Barros et al. (2013)
Organosolv	At 160 °C, Tween 80, 24 h	$FeCl_3$-catalyzed organosolv	100% of cellulose	<0.2 g furfural	Lignin removal and		

			conversion to glucose	and HMF/kg feedstock	hemicellulose hydrolysis	High cost of solvents recycling	Zhang et al. (2018)
Ionic liquids	AMIM-Cl with NH_4OH–H_2O_2–pretreated SCB	Dissolve cellulose	Glucan:57.3% Xylan: 18.0%	Furan	Less hazardous process chemicals	High cost, hygroscopicity a major concern	Zhu et al. (2012a); Luo et al. (2013)
Combined physico-chemical pretreatment							
Steam/hydrothermal	NaOH steam explosion	High lignin and hemicellulose solubilization	Reducing sugars (9.07 g/L)	Generates high toxic compound	Low cost with higher yield	Partialcellulose degradation	Silva et al. (2018)
Ammonia Fiber Explosion (AFEX)	Fiber explosion by ammonia (AFEX)	Break down lignin complex	Xylan conversion up to 95–98%	Generates fewer inhibitors	Increase digestibility of substrates	High-cost process	Krishnan et al. (2010)
Biological Pretreatment							
Penicillium echinulatum	1% (w/v) bagasse, 0.2% soy bran, incubated at 28 °C for 6 days	Enzymatic Saccharification	0.33 Uml^{-1}	NA	Mild reaction, high yields, less energy demand	Long incubation time	Camassola and Dillon (2009)
Ceriporiopsis subvermispora	25 g of bagasse suspension at a ratio of 500 mg of mycelium/kg	Enzymatic delignification and Saccharification	47% sugar-rich syrup recovered	NA	Mild reaction, high yields, less energy demand	Long incubation time	da Silva et al.. (2017)

fraction of time leaves cellulosic content intact while with broken interaction between components, with least generation of inhibitor in the process (Keshwani 2009). The pretreatment also reduced lignin and hemicellulose with an improved xylan and the lignin content (10.9%, 15.8%, respectively (de Souza et al. 2014). The microwave is the most employed method of pretreatment in a combination of chemical to improve further the fermentable sugar yield from biomass (Prasad et al. 2020).

Chemical Pretreatment Method of Sugarcane Bagasse

Various acids and alkali agents have been extensively applied over sugarcane bagasse to achieve a higher fermentable sugar yield from enzymatic hydrolysis of pretreated sugarcane bagasse (Karp et al. 2013). Sulfuric acid, hydrochloric, nitric, and phosphoric acids are the most studied acids for sugarcane bagasse pretreatment (Canilha et al. 2012; Hedayatkhah et al. 2013; Al Arni 2018; Prasad et al. 2020). The acid pretreatment is usually carried at a high temperature of 120–180 °C with a diluted acid concentration in range of 0.5–6% (Sabiha-Hanim and Abd Halim 2018). The biomass crystallinity has been reported to decrease significantly using dilute acid pretreatment of sugarcane bagasse with solubilization of hemicellulose fraction of biomass, thus improving cellulosic sugar release in upstream enzymatic hydrolysis steps (Canilha et al. 2012). Concentrated acid with 40–80% at low-temperature 30–60 °C has also been tested but with severe corrosiveness demerits and extreme inhibitors generation as a byproduct in hydrolysate (Sabiha-Hanim and Abd Halim 2018). Thus, the dilute acid method of pretreatment is the most preferred method of choice; however, with the associated drawback of inhibitor generation in the process such as furans, furfural, hydroxymethylfurfural, phenolics, carboxylic acids, formic, levulinic, and acetic acids (Palmqvist and Hahn-Hagerdal 2000; Prasad et al. 2018). Thus, to improve acid hydrolysis efficiency and minimize the process generated inhibitor molecules and other derivatives. Several critical factors, such as reaction temperature, pH, acid concentration, etc., have been optimized using various experimental design optimization tools to improve the process economics and improved enzymatic hydrolysis of pretreated biomass (Igbojionu et al. 2020). A recent innovative approach using acid pretreatment combined with acid-functionalized magnetic nanoparticles (MNPs) has been reported to enhance fermentable sugar yield from 15.40 g/L (Normal acid pretreatment) to 18.83 g/L (Acid-MNPs Treated) (Ingle et al. 2020).

Commonly applied alkali agents for sugarcane bagasse pretreatment include sodium hydroxide, calcium hydroxide (Rezende et al. 2011), potassium hydroxide (Grimaldi et al. 2015), aqueous ammonia, ammonia hydroxide (Paixão et al. 2016), in combination with hydrogen peroxide (Zhu et al. 2012a), NaOH in combination with $Ca(OH)_2$ (lime) (Hedayatkhah et al. 2013), and NaOH in combination with H_2O_2 (Ayeni et al. 2015). The alkaline pretreatment is most effective in delignification and hemicellulose solubilizing, thus improving the cellulose digestibility by enzymatic catalysis, thereby improving the overall release of fermentable sugar in hydrolysate (Sabiha-Hanim and Abd Halim 2018). The various factors critical to effective delignification by alkaline pretreatment methods include a precise combination of biomass loading and treatment conditions (Canilha et al. 2012). The sequential sugarcane bagasse (SCB) pretreatment was performed by using NaOH and hydroxy-methylation (HM). The result showed that as compared to NaOH pretreated SCB alone, HM increased glucose and xylose yield from 53.3 to 68.9% and 67.8 to 74.7%, respectively (Jin et al. 2020). Despite the effective energy process, the alkaline pretreatment process is cost-intensive due to a slow rate of reaction and a considerable amount of salt generation due to calcium hydroxide or lime and several process-generated by-product inhibitors of the ethanologenic microbial system (Sabiha-Hanim and Abd Halim 2018).

Combined Physical and Chemical Pretreatment of Sugarcane Bagasse

Numerous disadvantages are associated with the chemical pretreatment, such as energy and cost-intensive process and inhibitors toxicity from process-derived compounds. An alternative approach has been employed, combining mild reaction conditions with the chemical. Steam explosion is the most typical combined method of physicochemical pretreatment in which sugarcane bagasse is treated with steam under pressure (0.7 and 4.8 MPa) along with chemicals (acid/alkali) at high temperatures (160 and 240 °C). Thereby achieving a higher rate of hemicellulose solubilization but with low lignin removal. The maximum sugar recovery was reported by the steam explosion method of pretreatment of sugarcane bagasse at 180 and 215 °C with residence time 10–15 min (Mokomele et al. 2018).

In the ammonia fiber explosion (AFEx) method, biomass of sugarcane bagasse is exposed toAFEx at high temperature and pressure with a sudden pressure drop. Thus, it is deconstructing biomass to enhance fermentable sugar's probable release from enzymatic hydrolysis of such treated biomass (Krishnan et al. 2010). AFEx method of pretreatment has been reported to have the most scalability potential at a large scale due to various fractionation patterns this technology could generate into biomass after treatment leading to more remarkable process outcomes. AFEx is a fair process in terms of no ETP requirement post pretreatment since it is a dry-to-dry based process that actually vaporizes and separates the ammonia explicitly in the process. AFEx method has been reported to have achieved high delignification in operation and high sugar recovery with an optimized process variable such as biomass moisture content, ammonia loading rate, temperature, pressure, and residence time (Krishnan et al. 2010; Mokomele et al. 2018).

Biological Pretreatment

As mentioned above, several physical, chemical, and combined methods are used to pretreat biomass (Camassola and Dillon 2009). However, most methods are associated with few severe shortcomings, making them not perfect for biomass pretreatment. Yet, several strategies have been devised to date in search of practical techniques that are the most economical and eco-friendly. Biological pretreatment is another approach to reduce the lignin content of biomass. In this approach, microbial enzymes from cellulolytic and hemicellulolytic microorganisms are used. Among the various class of cellulolytic and hemicellulolytic microorganisms, the white-rot fungi have been reported to be the most effective microbial community in treating and solubilizing the lignin content of biomass so effectively. Peroxidases and laccases are the principal enzyme system utilized by these microbial systems to degrade and use the biomass's lignin component. Another class of microbial systems, i.e., brown-rot fungi, more often attack softwoods cellulose. While white- and soft-rot fungi attack and breakdown both cellulose and lignin in wood material (Beeson et al. 2015). The main advantages of using biological pretreatment include cost- and energy-efficient processes with the least toxic reaction environments of a microbial system that make the biological system of pretreatment an ideal strategy choice (Prasad et al. 2007). However, the biological system faces serious challenges of the microbial system's slow growth rate, lag period, and loss of carbohydrate in the process. However, serval process design and optimization strategies have also been employed to improve the biological pretreatment process to make these techniques more recognized at a large scale in days to come.

22.5.2.3 Saccharification of Sugarcane Bagasse

Saccharification is the process of converting complex carbohydrates into their monomeric form. The cellulose and hemicellulose component of pretreated sugarcane bagasse is further subjected to enzymatic hydrolysis for converting the polymeric structure of carbohydrate into glucose and xylose. In order to liberate fermentable sugar from pretreated bagasse cellulases and hemicellulases enzyme complex, i.e., endo-exo-glucanases, β-glycosylases, α-glucuronidase, β-xylosidases, etc., are used (Kucharska et al. 2020).

The mechanism of action of enzyme endoglucanase is primarily digesting β-1,4-glycosidic linkages of the cellulose molecule, thereby releasing oligosaccharide molecules. Simultaneously, exoglucanases catalyze cellulose conversion into a dimer, i.e., cellobiose and monomer, from the end of the cellulose chain. In contrast, β-glycosylases catalyze the conversion of cellobiose into glucose units. The enzyme endoxylanases catalyzes xylan's conversion into xylooligosaccharides, xylobiose, and D-xylose, whereas β-xylosidases catalyzes the conversion of xylobiose into xylose as monomeric pentose sugar (Singh et al. 2019).

In order to achieve a higher yield of fermentable sugar, several pretreatment strategies ranging from physical, chemical, and biological approaches have been optimized before the enzymatic hydrolysis step of biomass (Prasad et al. 2007). Thus, the optimized pretreated biomass is a potential raw material for liberating enhanced and improved enzymatic saccharification. However, several process optimization strategies have been employed to address these critical process challenges (Liu et al. 2015). For efficient biomass saccharification, the process condition, i.e., pH, temperature, enzyme, and biomass to loading rate, must be optimized (Khan et al. 2020).

22.5.2.4 Fermentation of Sugarcane Bagasse to Ethanol

Since fermentation involves microbial processes, the optimization of process conditions is a critical factor in achieving higher ethanol yield (Kucharska et al. 2018). Also, fermentation efficiency is hampered by several inhibitor molecules produced during the pretreatment steps, which is still critical to overcome such

Table 22.4 Examples of sugarcane bagasse pretreatment and its effect on SSF and ethanol production

Pretreatment method	Microbes	Initial Sugar (g/L)	Fermentation conditions	Ethanol yield (g/L)	References
Steam explosion,temperature:195 °C kept for 7.5 min.	*S. cerevisiae*	60.4	SSF,tempatature: 35 °C, 150 rpm time: 48 h	18.3	Neves et al. (2016)
Alkali-pretreated with NaOH:15%, temperature: 175 °C	*S. cerevisiae- LBM-1*	24.0	SSF, at 37 °C, rpm: 180, time: 10 h	8.8	de Carvalho et al. (2016)
Pretreated with NH_4OH-H_2O_2temperature:140 °C kept for 60 min	*S. cerevisiae SHY07-1* and *Pichia stipitis*	13.9	SSF for120 h	14.1	Zhu et al. (2012b)
Pretreated with dilute HNO_3,temperature:100 °C, kept for 30 min	*Pichia stipitis 3498* and *S. cerevisiae VSI 1011*	79.43	32 °C, 36 h. at 120 rpm	31.01	Santosh et al. (2017)
0.29 M of NaOH, 0.78% (v/v) of H_2O_2, kept for 9.95 min	*Scheffersomyces stipitis* NRRL-Y7124	Glucose:60, xylose: 25	Temp- 30 °C and 200 rpm during 48 h	31.50	Hilares et al. (2018)

challenges in improving overall process economics for ethanol production from sugarcane bagasse (Bussamra et al. 2020). Therefore, it is essential to develop an efficient synergistic enzymatic cocktail system, where the pretreatment step can be combined with the saccharification and fermentation step. Such simultaneous saccharification and fermentation (SSF) mode can improve the whole ethanol production process efficiencies (Gubicza et al. 2016; Fahmy et al. 2019; Prasad et al. 2020). Examples of some of the critical studies on sugarcane bagasse pretreatment and its effect on simultaneous saccharification and fermentation (SSF) and ethanol production (Saha et al. 2019) are shown in Table 22.4.

22.6 Conclusion and Future Prospect

Worldwide, sugarcane crops are grown extensively and have great potential to produce ethanol due to the highly diversified product and byproduct, especially raw juice, molasses, and fibrous bagasse. The scientific community and policymakers currently focus on ecofriendly and wise management of its vast amount of bagasse to produce bioenergy. Several pretreatment technologies are available to achieve high ethanol yield via economically feasible pretreatment, enzymatic hydrolysis and fermentation from bagasse. Many challenges exist during the critical step in bioethanol production, such as physicochemical and biological pretreatment followed by enzymatic saccharification. However, extensive research to develop cost-effective, innovative bioconversion pretreatment technologies choices and the proper selection of efficient methods are required. The effective delignification, inhibitory compound removal with low sugar loss, and the utilization of simultaneous saccharification and fermentation (SSF) can make it more successful and valuable for economically industrial ethanol production.

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Emerging Policy Concerns for Improving Input Use Efficiency in Agriculture for Global Food Security in South Asia

23

Manjeet Kaur, Amit Guleria, Jasdev Singh, H. S. Kingra, and Sukhpal Singh

Abstract

South Asian region comprises of Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. It constituted more than one-fourth population of the developing world and about 72 percent of them resides in rural area. Its population density is high as compared to other developing countries. Its agro-ecological characteristics are diverse in nature which allows farmers to grow a wide range of crops and raise different livestock species. Over time the share of GDP from agriculture has declined in the region in general but with different magnitude between the countries. The workforce engaged in agriculture also declined resulting into unemployment within the rural sector of Asian region. The land-use pattern showed more than 50 percent decline of the arable land per person between 1961 to 2018; whereas cropping intensity increased from 128 to 143 percent and also the increase in area under forest was observed. The economic liberalization policies introduced in 1991 had significant impact on South Asian Countries trade scenarios through making imports cheap. The chapter encompasses country-wise detailed information on agricultural growth rates, land-use pattern, cropping pattern, input use, trade scenario, subsidies, etc., for the South Asian region. It is hypothesised that at the present level of agricultural development and input use efficiency, economic policies, subsidies and their impact on natural resources there possessed little scope to expand food production to meet the requirement of growing population of the region. Emerging governmental policies for improved livelihood and assured global food security in South Asia were discussed to meet these challenges.

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Keywords

Agriculture · Sustainability · Growth rate · South Asia · Input use efficiency

Abbreviations

CAGR	Compound annual growth rate
FAO	Food and Agriculture Organization
FL	Family labour
GCA	Gross cropped area
GDP	Gross domestic product
Ha	Hectare
HVCs	High value crops
MSP	Minimum support price
MT	Metric tonnes
OECD	Organisation for Economic Co-operation and Development
UN	United Nations
WTO	World Trade Organization

23.1 Introduction

South Asian region comprises of Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. This region has more than one-fourth population of the developing world, of which, 72 percent (970 million) lives in rural areas. The number of farm households in South Asia is around 150 million with 751 million individuals. The rural population density of this region has reached to 1.89 persons per ha which is much more as compared to any developing region with limited area of 514 million ha (Dixon et al. 2001) which leads to severe pressure on natural resources.

In South Asia, 94 percent of suitable agricultural land has been already cultivated (FAO 2002), leaving no space for expansion. The region's area under annual cultivation and permanent crops is forecasted to be 213 million ha (41 percent of total land area), with only a minor rise anticipated by 2030 (FAO 2017). Furthermore, new land area mostly comes from pasture and forest land, implying substantial investments as well as some foregone development. Since the late 1980s, the majority of South Asian countries have been experiencing structural reforms. They are increasingly integrating trade liberalization into their economic framework. Agriculture's globalization, on the other hand, has provided these countries' agrarian markets with new problems and prospects. While there are fears that the influx of subsidised cheap imports from developing countries would affect their agriculture, there is evidence that these countries will increase agricultural exports, especially of high-value and labor-intensive commodities. This appears to open up a window of opportunity at a time when South Asian agriculture is seeing its holdings diminish, slow technical advancements in staple crops, fall in agricultural investment, and rise in natural resource depletion.

South Asia's agricultural systems have been influenced by the region's overall lack of water supplies and their regional distribution. Irrigated land area in the region is projected to rise rapidly from 85 million ha to 95 million ha (44 percent of cultivated land) by 2030 (Alexandratos and Bruinsma 2012). Owing to the high cost of installing new, environmentally friendly irrigation systems, as well as donor reluctance to finance major irrigation schemes, governments may choose to concentrate on modernising existing irrigation systems and improving water quality. Participatory control or user ownership transition, improved operating system architecture, enhanced ventilation, and cost recovery would all be part of this. Water availability can also be improved by enhancing runoff conservation and utilisation, expanding water storage capacity, and combining ground water and surface water usage. Conservation agriculture, which includes mulching, bunding, wind breaks, etc., can help farmers save more water on their farms.

South Asian region marked by inequities in food and nutritional stability, a decreasing agricultural yield has emerged as a major concern in recent decades. Current fertilizer use patterns, depending heavily on nitrogenous fertilizers, have emerged as major roadblocks in improving fertilizer effectiveness in the region, alongside weak nutrition management, a shortage of complementary inputs, declining soil productivity, and insufficient marketing, and distribution networks. This chapter discusses importance of agriculture in terms of its share in GDP, employment in agriculture, labor productivity, input use efficiency and cropping pattern in South Asian region. It is hypothesised that at the present level of agricultural development and input use efficiency, economic policies, subsidies and their impact on natural resources there possessed little scope to expand food production to meet the growing population of the region. Emerging governmental policies for improved livelihood and assured global food security in South Asia are discussed at the end of the chapter.

23.2 Dynamics of Agricultural Growth and Structural Changes in South Asian Region

Agriculture is primary source of economic development in South Asia. Agriculture provides income, jobs, and food security to a significant portion of population. The share of agriculture in GDP declined from about 30 percent in 1970 to 17 percent in 2017 in South Asia according to FAO estimates (Fig. 23.1). This decline in the share of agriculture was due to more significant growth of other sectors as compared to agriculture. During this period, the agricultural GDP grew only from 0.13 to 0.45 million US$, on contrary 11 times increase in the GDP from other sectors was observed. South Asia's agricultural production is rising in recent years. The compound annual growth rate (CAGR) of agricultural GDP was worked out for the south Asian countries and shown in Fig. 23.2. It was evident from the figure that growth in

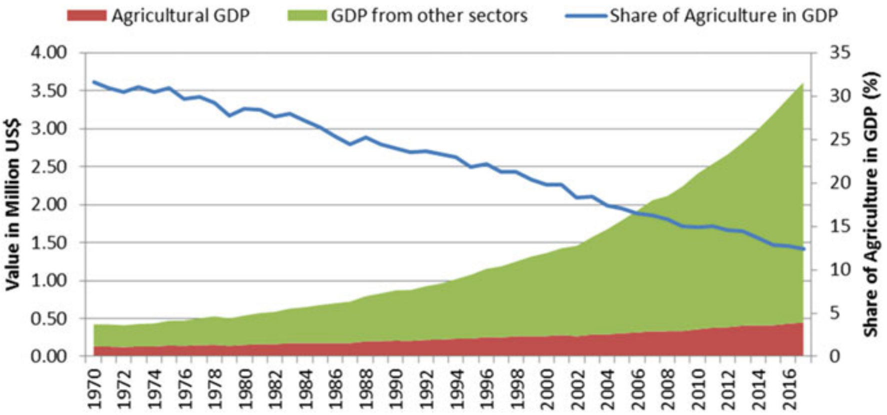

Fig. 23.1 Share of agriculture in GDP at 2010 prices of South Asia

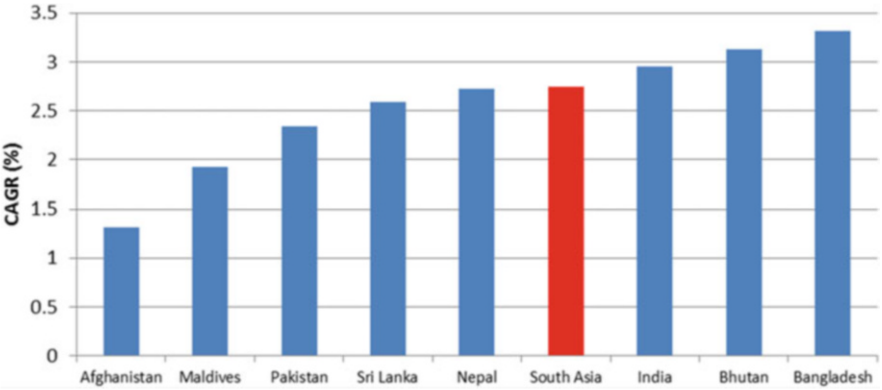

Fig. 23.2 Compound annual growth rate of Agricultural GDP among south Asian countries, 1970–2017

agriculture GDP in Bangladesh, Bhutan, and India was more as compared to other south Asian countries and overall average of the South Asia. The growth rate was minimum in the Afghanistan among south Asian economies. It is evident from Fig. 23.3 that Nepal has the highest share in agricultural GDP, i.e., 32 percent as compare to other South Asian nations.

23.3 Agricultural Trade in South Asian Region

The agriculture trade plays a significant role in providing the food security to South Asian Population. Country-wise export and import scenario of agricultural products varies within South Asia countries. It was evident from Fig. 23.4 that Pakistan and Nepal are the only South Asian countries with a share of exports greater than 50 percent of overall agricultural trade in the last decade, indicating that the value

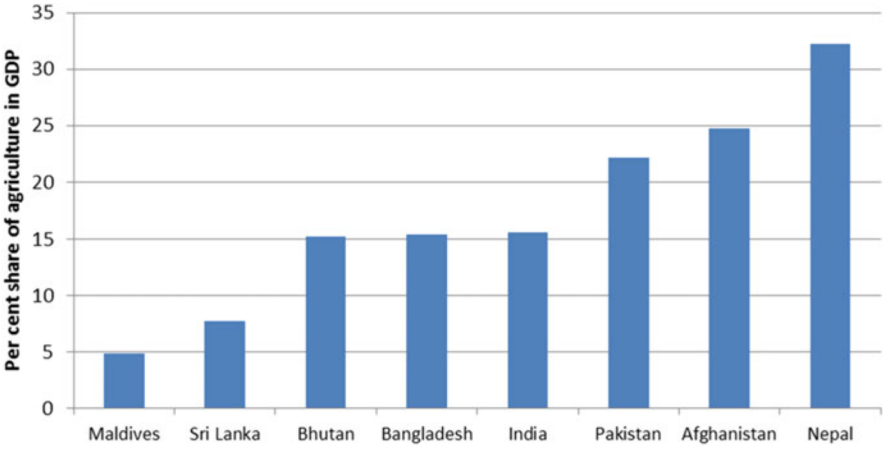

Fig. 23.3 Share of agriculture in GDP among South Asian countries in last decade

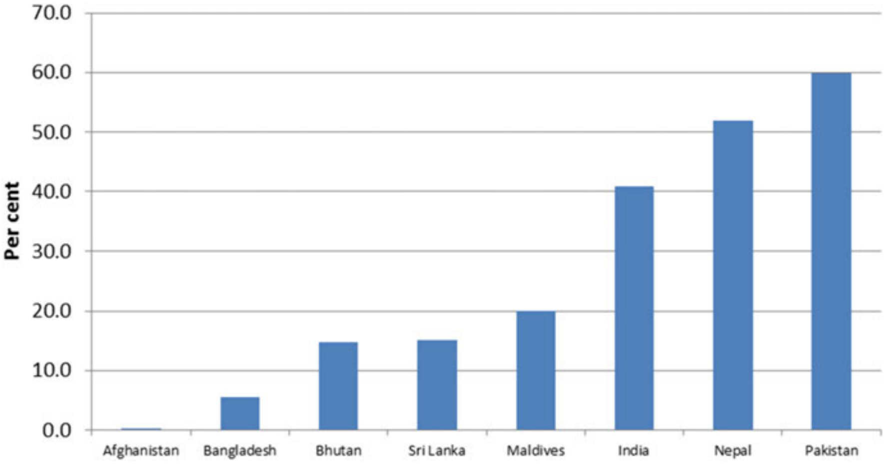

Fig. 23.4 Share of export in total agricultural trade (export + import) among South Asian Nations during 2010–18

of exports exceeded the value of agricultural imports. In India, the share of export was accounted about 41 percent of total agricultural trade indicates remaining 59 percent was imports. While trade barriers such as lack of comparative advantage, less diversification in export products, and trade facilitation are critical, supply restrictions continue to be the most significant, despite progress in the removal of tariff and non-tariff barriers. The value of total agricultural trade significantly increased from four thousand million to 56 thousand million US$ from 1961–1980 to 2001–2018. The share of agriculture trade in the total merchandise trade was also

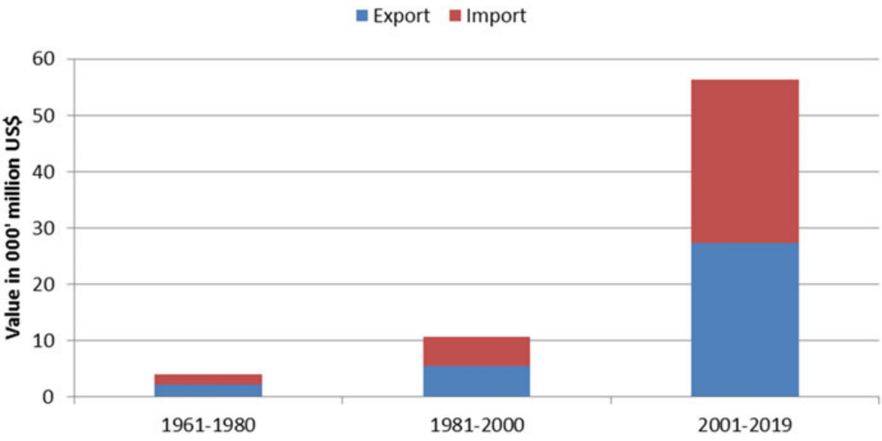

Fig. 23.5 Dynamics of agricultural trade of south Asia

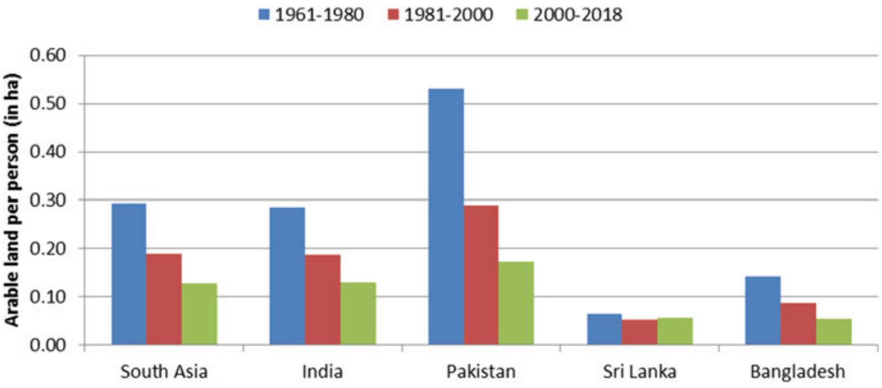

Fig. 23.6 Trend of Arable land per person in South Asian Nations (Source World Bank)

low due to agriculture being a very sensitive issue in some of South Asian nations (Fig. 23.5).

23.4 Arable Land in South Asian Region

Land resources are important for agriculture and rural development, and they are inextricably related to global concerns including food, poverty and malnutrition, climate change adaptation and mitigation, natural resource degradation and depletion, all of which impact the livelihoods of millions of people in rural areas across the world. Arable land per person is an important indicator of per capita availability of land suitable for agriculture. It is evident from Fig. 23.6 that arable land is continuously declining over time in almost all the countries of the South Asia except Sri

Lanka. In South Asian region, the arable land per person in the time period of 1961–1980 was 0.29 ha which decreased to 0.13 ha in 2000–2018. Among South Asian nations, the significant decline in the arable land per person was observed in Pakistan where per capita availability of arable land decreased from 0.53 ha to 0.17 ha over a period of time. On contrary, in Sri Lanka the per capita arable land was almost same during this period.

23.5 Land use pattern in South Asian Region

Land resources of a nation are not only dependent on the extent of its geographical area but also on its land-use pattern. Land utilization pattern is an indicator of the agricultural development status of the region and has been classified into five categories namely, crop land, forest land, inland waters, pastures, and other land. Out of five categories, share of forest land has registered an increasing trend and remaining four categories have undergone decline as shown in Fig. 23.7. The increase in the forest land can be accounted by increase in the demarcated area under forest rather than an actual increase in the forest cover in the South Asia. It is evident from the figure that there is decline in crop land, inland waters, pastures and other land by 0.3, 0.1, 1.97, and 2.07 percent, respectively and rise in the forest land by 4.5 percent.

It is observed from Fig. 23.8 that land-use pattern varied greatly among South Asian countries. It is found that share of crop land is the highest in Bangladesh, i.e., 58 percent followed by India (52%) and Pakistan (39%). Percent share of forest land is found maximum in Bhutan, i.e., 70 percent followed by Nepal (40%) and Sri Lanka (32%). The proportionate area under inland water is found maximum in Bangladesh, i.e., 12 percent followed by India (9%) and Sri Lanka (5%). The percent area under pastures is the highest in Afghanistan, i.e., 46 percent followed by Nepal (12%) and Bhutan (10%).

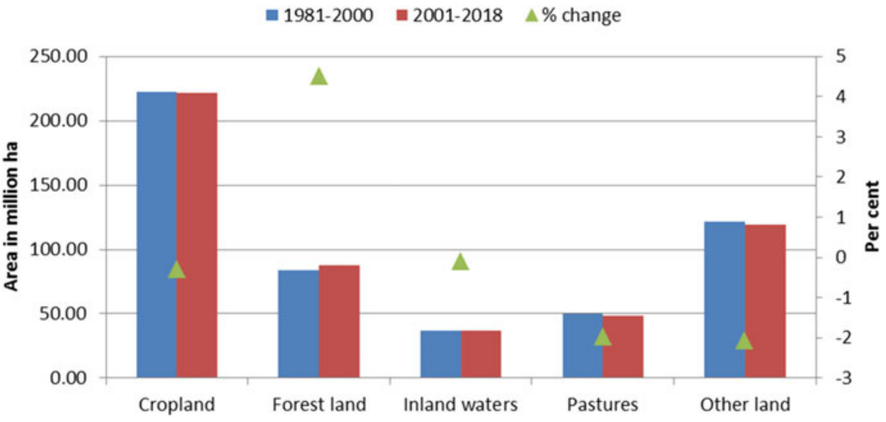

Fig. 23.7 Change in land use patter of South Asia

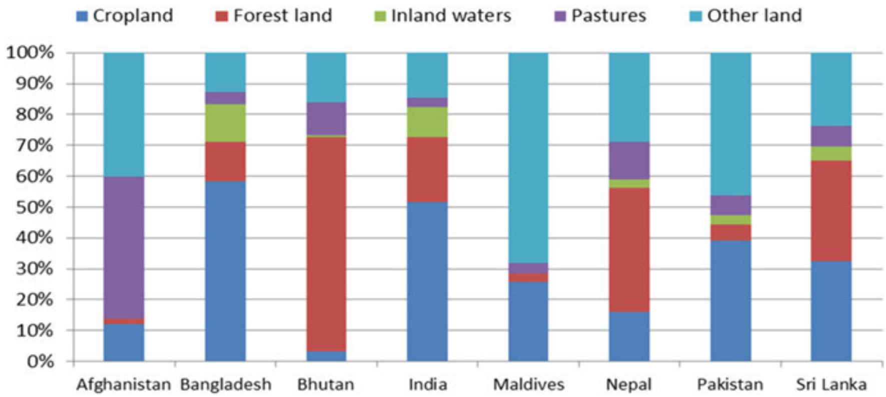

Fig. 23.8 Land-use pattern of south Asian countries for 2000–2018 (in percent)

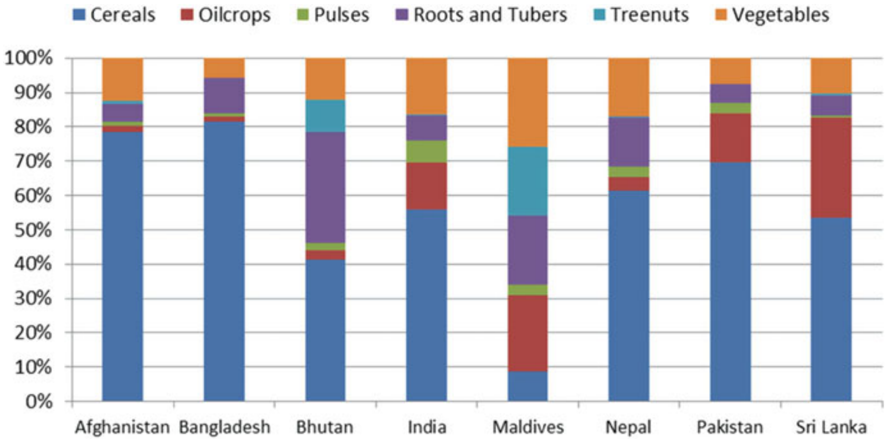

Fig. 23.9 Cropping pattern of south Asian countries for 2000–2018 (in percent)

23.6 Cropping Pattern in South Asia Region

Cropping pattern is a dynamic concept because it changes over space and time. In other words, it is a yearly sequence and spatial arrangement of sowing and fallow on a given area. In South Asia, the cropping pattern is determined by rainfall, climate, temperature, soil type, and technology. Cereals dominate in all South Asian countries except Maldives. In cereals, wheat paddy cropping system is most common in this region. It is evident from Fig. 23.9 that the highest proportion of cereals crops are cultivated in Bangladesh, i.e., 81 percent followed by Afghanistan (78%) and Pakistan (69%). About one-fourth of gross cropped area in Maldives is under vegetables and cultivation of vegetables is also prevalent in Nepal (17%) and India

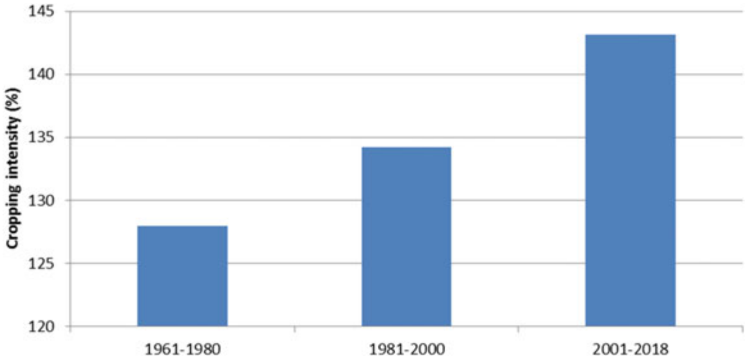

Fig. 23.10 Cropping intensity (%) of south Asia

(16%). Bhutan (33%) leads in percent share of area under root and tubers among South Asian countries. Over the period of time, cropping intensity in South Asia is improving continuously. It is observed from Fig. 23.10 that the cropping intensity is around 128 percent in 1961–1980 and reached to 143 percent in 2000–2018 in South Asia.

23.7 Employment and Labour Productivity in Agriculture sector in South Asian Region

Despite the decline in the share of agriculture in GDP from 30 percent in 1970 to 17 percent in 2017 the employment within agriculture sector remained more than 40 percent in many South Asian countries. Over time share of agriculture in employment among South Asian nations is presented in Fig. 23.11. It is observed that share of agriculture in employment declined in 2010–2017 as compared to last decade 2000–2010 in the region. It is found that the decline is more significant in Nepal, i.e., from 71 to 22 percent in last two decades. Decline in employment in agriculture is from 16 percent in India, 10 percent in Bangladesh, 4 percent in Bhutan and Sri Lanka and 2 percent in Pakistan. This indicates that many countries have misallocated labor and have not been effectively adjusting "surplus labour" from agriculture into the rest of the economy. As a result, agricultural incomes have been declining over the years.

Value added from agricultural sector depends upon size of the agrarian economy, area and productivity of farmland, labour force engaged, climatic stresses, public and private investment. Agricultural value added per worker is an indicator to compare the agricultural situation of South Asian nations and also shows the relative position of agricultural income. This is influenced by land productivity, capital formation (machinery and irrigation), investment per worker, suitable climatic conditions, and technology adopted. The detail of agricultural value added per worker is presented in Fig. 23.12. It is observed that maximum agricultural value per worker is found in

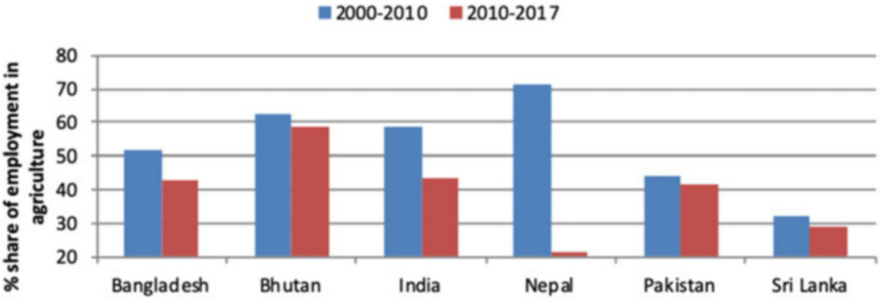

Fig. 23.11 Percent share of employment in agriculture of South Asian Nations (Data were not available for Afghanistan and Maldives)

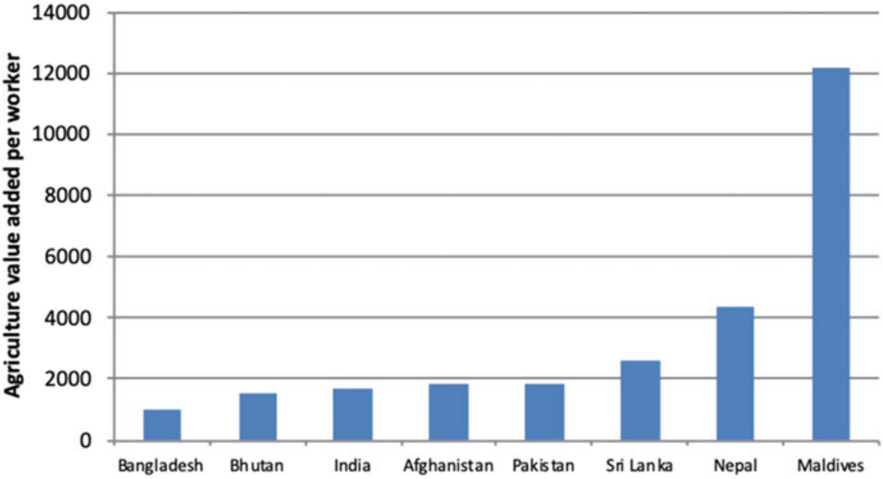

Fig. 23.12 Agricultural value-added per worker (in US$, 2010 prices) of South Asian Nations during 2012–2017

Maldives among South Asian nations, i.e., around 12,000 US$. In countries like Bangladesh and Bhutan, agricultural value per worker is less which indicates the relatively poor economic condition of agricultural workers. Effective policies and initiatives are needed to affect a convergence of labour productivity through agriculture, manufacturing, and services in order to maximise agricultural productivity. For example, such measures can remove regulations that restrict the flow of labour and capital through industries. Importantly, absorbing agricultural labour would necessitate systematic attempts to increase its employability in other sectors: workers will need to be retrained to perform new tasks, operate more complex machinery, and transition to manufacturing workers that can properly use skilled resources in rural areas.

23.8 Fertilizer Use in South Asian Region

Imbalance in application of fertilizer is one of major problem in the South Asia. Subsidies to increase the use of fertilizers are given by many South Asian countries which helped farmers to increase their productivity in general and profitability in particular. Country-wise average utilization of nutrient fertilizer especially nitrogen, phosphorous, and potassium is presented in Table 23.1. It is evident from the table that maximum per hectare utilization of fertilizer is observed in Bangladesh in the period of 2000–2018. In Bangladesh, the usage of nitrogen based fertilizer was 128.95 Kg per ha while, it is 39.70 Kg per ha and 25.92 Kg per ha for phosphorous-based- and potassium-based fertilizers, respectively. Usage of nitrogen-based fertilizers is quite high in Pakistan, India, and Sri Lanka, i.e., 90.93, 84.17 and 81.31 Kg per ha, respectively. The usage of phosphorus-based fertilizer is the highest in Sri Lanka among South Asian countries, i.e., 29.53 Kg per ha. Over the period of time the utilization of the fertilizer is increasing in South Asia as shown by Fig. 23.13. It is observed that in South Asia, the average per hectare usage of nitrogen-based fertilizer increased from 15 to 82 Kg from period I (1961–1980) to period III (2000–2018). While, in case of phosphorous- and potassium-based fertilizer the trend is similar. So, there is a need to increase the investments in new soil intelligence framework that integrates high-resolution digital soil maps with efforts

Table 23.1 Average usage of nutrient fertilizer (in kg per ha) among South Asian countries in 2000 to 2018

Particulars	N	P2O5	K2O
Afghanistan	29.35	4.72	0.03
Bangladesh	128.95	39.70	25.92
Bhutan	7.86	2.69	1.33
India	84.17	34.22	13.82
Maldives	22.43	7.18	7.61
Nepal	18.10	7.87	0.75
Pakistan	90.93	24.99	0.82
Sri Lanka	81.31	21.81	29.53

Source: FAO 2020

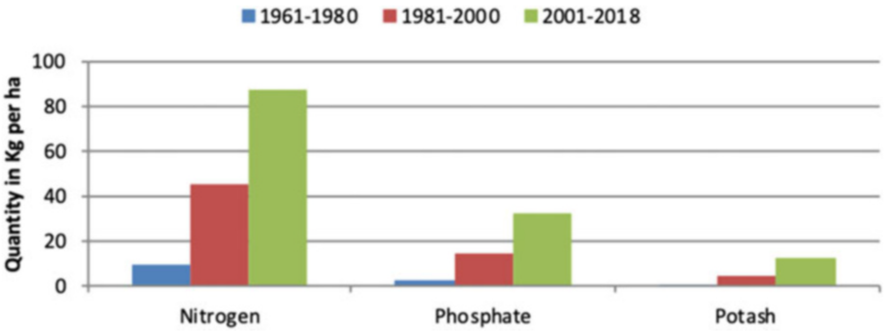

Fig. 23.13 Trend of fertilizer usage in south Asia

to create personalised recommendations and fertilizer blends which in turn could aid fertilizer policy reforms in South Asian region. By factoring in fertilizer costs and crop prices in the generation of advice, maps can also help farmers increase their returns. Soil intelligence systems are likely to be feasible in India and Bangladesh, thanks to the comparatively rich data soils infrastructure accessible through national research programmes (Kishore et al. 2021; Kumar et al. 2021).

23.9 Pesticide Use in South Asian Region

Pesticide misuse in agriculture (including overuse, inappropriate usage, and the use of outdated products) is a global concern that has a particularly negative effect on vegetable production systems in low lands. Usage of pesticides is comparatively higher in high-value crops than cereals. Farmers and their families are at high risk due to unsafe pesticide mixing, spraying, and storage procedures. Usage of the pesticides especially fungicides is increasing over a period of time in South Asia as shown in Fig. 23.14. The utilization of fungicides was around 50 g per ha in the period I (1991–2000), which increased to 120 g per ha in period III (2011–2018). On contrary, demand of herbicides is almost stagnant over the same period, while per hectare usage of insecticides is declining from period I to period III. This declining trend indicates that farmers of South Asia are now aware of harmful effect of over-utilization of insecticides. Among different South Asian countries, percent share of fungicides in the total pesticides consumption is observed to be maximum in Bangladesh followed by Nepal. The utilization of herbicides is observed to be more in Bhutan and Sri Lanka. While, the proportionate share of insecticides is found high in Maldives and Pakistan (Fig. 23.15).

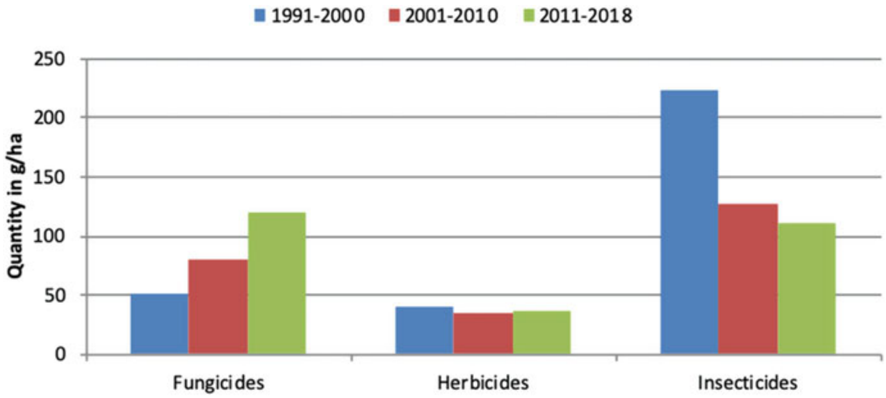

Fig. 23.14 Trends of pesticides usage in South Asia

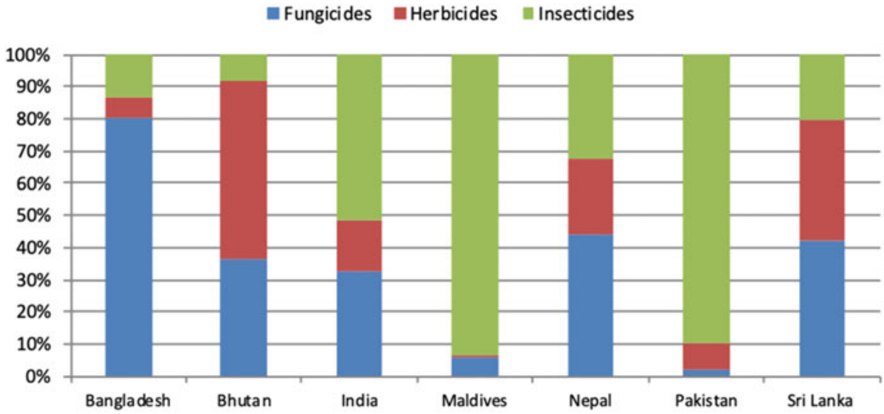

Fig. 23.15 Share of different pesticides in total usage among South Asian Nations

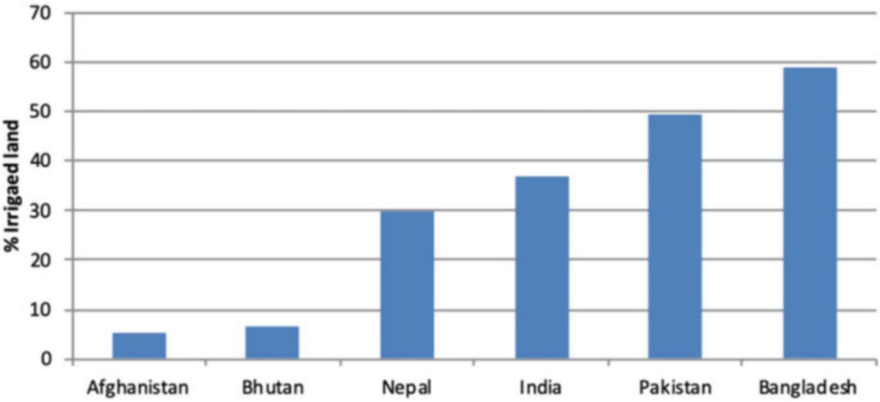

Fig. 23.16 Share of irrigated land in south Asian nations

23.10 Percent Area Irrigated in South Asian Region

Irrigation is critical for food security and economic growth in South Asia, but its utilization can be improved through a management mechanism to capture and distribute surface water, and judiciously controlling groundwater irrigation. South Asia has the highest percentage of irrigated agriculture, despite being one of the world's most heavily populated region irrigated and rain-fed crops co-exist in every village, with rain-fed crops accounting for 58 percent of South Asia's cultivated land and irrigation rates hovering over 40 percent. Among different South Asian nations, Bangladesh has the highest percent area under irrigation, i.e., around 59 percent, followed by Pakistan (49%) and India (37%) in the last decade as show in Fig. 23.16.

There is need of good governance and political maturity for improving policy decisions towards increasing the water use efficiency for country's progress.

23.11 Area under HVCs in South Asian Region

Area under high-value crops (HVCs) is one of the indicator of the agricultural performance of the nation. High-value crops are those crops which are perishable in nature, sold in specialized market and have more value than cereals. Diversification into HVCs can support poor farmers and landless laborers by increasing both production and job opportunities. It will help the vulnerable in rural and urban areas by expanding the non-farm economy and making nutrient-dense food more readily accessible. Diversification also encourages the vulnerable by increasing their access to decision-making systems, increasing their collective action potential, and reducing their exposure to shocks by wealth accumulation. Diversification into HVCs possibly will help South Asia countries in poverty reduction, long-term growth, and food security. The share of high-value crops in gross cropped area among South Asian nations for the period of 2000–2018 is presented in Fig. 23.17. It is evident from the figure that the percent share of HVCs is the highest in Maldives (26%) followed by Nepal (17%) and India (16%). There is need to increase the area under high-value crops especially by small and marginal farmers and also provide them opportunity in market and knowledge of technical know-how in relation to quality standards. Besides the continued position of high-yielding rice and wheat varieties in South Asian countries, diversification is the need in favour of high-value crops for agricultural development. Climate, soils, and other agro ecological characteristics vary greatly across South Asia (Joshi et al., 2004; Meena et al. 2020). Farmers in

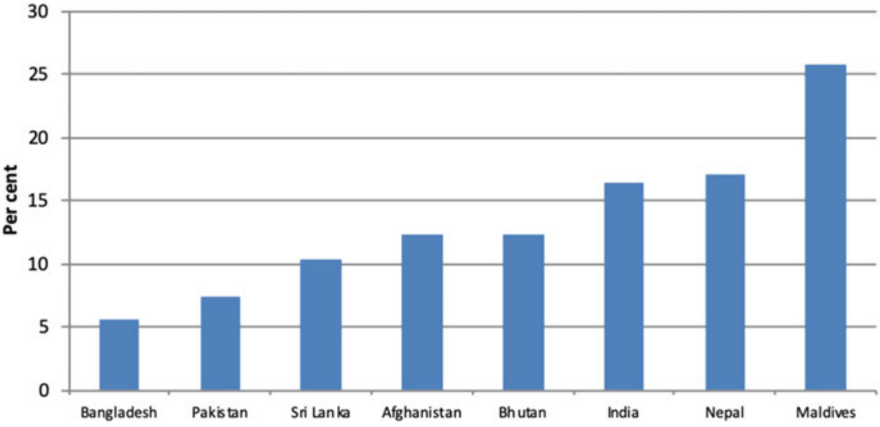

Fig. 23.17 Share of high value crops in gross cropped area among south Asian nations for 2000–2018

South Asia can grow a variety of vegetables, raise a variety of livestock, and fish species due to its diverse agro-climatic condition.

23.12 Subsidies in Agriculture

Subsidies are a form of assistance provided for a variety of purposes, including promoting regional and rural growth, supporting jobs and wages, and assisting with the transition to shifting economic, social, and environmental conditions (OECD 2003). However, such funding may have detrimental consequences that could go unnoticed or perhaps overlooked during the policy-making process. Carbon tax rebates encourage the usage of fossil fuels, while commercial fishing funding may contribute to overfishing, and agricultural support may lead to over use of pesticides and fertilizers. Researchers began to point out the negative impact of subsidies on electricity consumption, the loss of marine fish populations (Kumar and Meena 2020), and soil degradation, crop waste, and deforestation in the mid- to late-1980s and afterwards (Reichelderfer 1998; Tobey and Reinert 1991; Anderson and Bird 1992; Runge 1996; Yadav et al. 2020).

There are no accurate figures of the value of subsidies that are detrimental to the environment (OECD 1998, 2001, 2005). Typical annual impressionistic estimates vary from $500 billion to $2000 billion. It is tough, but not impossible, to extrapolate evidence for environmentally damaging agricultural subsidies. According to one study, OECD (Organisation for Economic Cooperation and Development) nation subsidies to agriculture that were environmentally destructive amounts to more than $300 billion a year in the late 1990s (Beers and Moor 2001). In light of the mounting facts, the policymakers have become increasingly aware of the environmental damage that subsidies can cause over the last two decades (Steenblik 2003; Kumar et al. 2018). As a result, a number of countries have vowed to overhaul subsidies that could jeopardise long-term growth. These also included (non-binding) promises to amend or abolish subsidies that damage biodiversity (UN 1992), promote fossil fuel use (UN 1998), or facilitate over-fishing (UN 1998) (FAO 2002). Similarly, the Plan of Implementation of the World Summit on Sustainable Development (2002) calls for the restructuring, phasing out, or abolition of subsidies that have harmful environmental consequences and are therefore incompatible with sustainable development in many areas. Ministers of Trade advised the World Trade Organization's (WTO) Committee on Trade and Environment in sub-paragraph 32(i) of the Doha Ministerial Declaration to "pay special attention to: those circumstances in which the removal or reduction of trade barriers and distortions will favour trade, the environment, and development" (WTO 2001). Given the large (and growing) number of foreign commitments to minimize subsidies that not only encourage environmentally harmful practises but also reduce economic productivity, one would fairly expect countries to follow up with their commitments and even aim to eliminate subsidies quickly. International development, on the other hand, has been sluggish. Few nations, let alone unilateral reforms, have followed through on their foreign obligations. Perhaps this is unsurprising. Subsidies, while in existence, are typically difficult to remove for sectorial, economic and domestic political purposes. Indeed, foreign practice has shown how difficult it is to change subsidies (OECD 2005).

Several developed and emerging countries have been offering subsidies to resource-intensive sectors such as irrigation, fishing, and manufacturing. However, the allocation of input and export incentives has resulted in overproduction and deforestation, as well as overexploitation of natural resources, posing a significant danger to environmental sustainability. One of worry is that, current WTO talks is still pending w.r.t the subsidies with potentially adverse environmental consequences which has not decreased in recent years.

23.13 Opportunities for Improved Livelihood in South Asian Region

Stagnation in the rural economy tends to push marginalized people into cities. Increases in urban population that are not well-managed harm economic development and urban welfare, and they become a source of fierce rivalry and dispute for resources. These tensions overwhelmingly impact vulnerable people living in underserved informal settlement.

The difference between rural and urban areas, on the other hand, is quite obvious. More people are migrating or commuting between rural and urban areas on seasonal basis, for example, as farmers for half the year and garment workers for the other. Agriculture is a means of revenue for city dwellers and, on the other hand, agriculture benefits from remittances from cities. Poor people's livelihood plans are complicated. A livelihoods viewpoint adds to our understanding of how agricultural development will help to ease hunger and vulnerability:

- Farming provides half of the household income for poor people in rural areas, particularly those who do not own land. This involves living on other people's crops. Agriculture's relative value varies depending on geography and resources, but there are no hard and fast rules for how it is so. Poor households in both favoured and marginal areas rely more heavily on non-farm income, especially remittances from abroad (Alexandratos and Bruinsma 2012).
- Agriculture provides both wages and food for home use (either through wage work on farms or through the selling of produce). Households that rely on agriculture for self-sufficiency are a unique case in the food security debate since their consumption is also their production.
- Farming will assist in the recovery of livelihoods and provide a safety net for households during economic downturns.
- Expansion in agriculture also creates a market for others resources. In villages and small towns, the fortunes of local merchants, brickmakers, carpenters, and food sellers are inextricably linked to the fortunes of local agricultural enterprises. Thus looking into the importance of agriculture in livelihood security of rural and urban people and agricultural scenario in South Asian region.

23.14 Emerging Governmental Policies for Improved Livelihood and Assured Global Food Security in South Asian Region

In South Asia, about 94 percent of land is suitable for agriculture but there are some major constraints observed in agriculture development viz. shrinking size of land holding, decelerating technological advances in staple crops and declining investment in agriculture. The share of agriculture in GDP is continuously declining over the period 1970 to 2018 from 32 to 13 percent of South Asia. The CAGR of agricultural GDP is around only 2.7 percent for this region. More than 50 percent share of export in total agricultural trade is only found in Nepal and Pakistan. In this region, the arable land per person in the time period of 1961–1980 is 0.29 ha which decreased to 0.13 ha in 2000–2018. It is found that share of crop land is the highest in Bangladesh, i.e., 58 percent followed by India (52%) and Pakistan (39%). Over the period of 1961 to 2018, the cropping intensity was continuously improving, i.e., 128 to 143 percent. The share of employment from agriculture is continuously decline in South Asia. Agricultural value added per worker is found to be the highest in Maldives, i.e., around 12,000 US$ while, the lowest in Bangladesh, i.e., 1000 US $. The application of nitrogen based fertilizer and fungicides are continuously increasing in this region, while in application of insecticides, there is a declining trend. Bangladesh have the highest percent irrigated area while, Afghanistan have the lowest. Area under HVCs is highest in the Maldives and lowest in Bangladesh. The subsidies for agriculture have positive relationship with natural resource degradation. Subsidies skew market costs and resource allocation choices, affecting the volume of products and services generated and consumed in a given economy. So, make the agriculture productive and sustainable for the generations to come. Some of policy recommendations for improved and sustainable livelihoods are discussed below:

- There is a need of technological innovations in agriculture in South Asia to increase the agricultural productivity and raise farmers' income. There should be rational allocation of inputs and which helps in reasonable investment in agricultural machinery and thereby, overcome the adverse impact of over investment and diseconomies of scale.
- There is need to speed-up the process of agriculture diversification and raise the area under high value crops to increase agriculture value added per worker. So, prerequisite of proper strategy and institutional reforms of south Asian economies will integrate the markets and production processes.
- There is need to enhance the domestic production to overcome the problems like rapid increase in population, decreasing yield and livelihood security which helps to sustain the food security.
- Assisting in the development of alternate rural service models, such as technology, knowledge, banking, insurance, and business guidance, as well as rural utilities, such as irrigation. These must be delivered at the required scale, be affordable, and be based on the needs of the customer. Effective models are most

likely to include the private sector and civil society, with the government playing a smaller part in implementation.

- Creation of an enabling climate for private sector growth that takes into account the needs of agriculture-based development goals and is pro-poor. Small-scale agriculture will benefit from initiatives like the production-linked incentives, business linkage challenge fund, which encourages private sector investment.
- Effective markets and systems that help farmers manage the uncertainties associated with agricultural production through, for example, commodity price risk management mechanisms for small farmers and other forms of social protection.
- Ensuring that rural issues are considered when developing national and subnational policies concerning agricultural production, markets, and land usage.

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Estimating the Input Use Efficiency of Rice Farmers in Bangladesh: An Application of the Primal System of Stochastic Frontier Approach

24

Subir Bairagi, Mazbahul Ahamad, and Khondoker Abdul Mottaleb

Abstract

Rice is the staple food for half of the world's population, and with the increase in population, it will be necessary to supply more rice in the future. However, sustainable rice production has been threatened by ever-declining natural resources and the misuse and overuse of inputs such as pesticides and fertilizers. Therefore, attaining input use efficiency in producing rice is imperative to ensure food security and sustainable development in the world. Using primary data collected from Bangladesh, this chapter econometrically estimates input use inefficiencies for rice production in northwest Bangladesh. The results suggest that the mean technical inefficiency is approximately 29%, which means that nearly one-third of rice production is foregone. The main drivers of this technical efficiency are the adoption of submergence-tolerant (Sub1) rice varieties and pesticides application. Therefore, inefficiencies can be reduced by large-scale diffusion of Sub1 rice varieties and the implementation of variable pesticide recommendation guides. The results also indicate that the average technical inefficiency alone increases input demand and costs by approximately 5.0%.

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Input allocative efficiency leads to an under-use of seed and fertilizer relative to labor, which increases the actual cost by 6.3%. This suggests that the rice sector in Bangladesh is still a labor-intensive industry. Hence, this chapter recommends enhancing small-scale mechanization for farming activities, which can reduce rice production costs in Bangladesh.

Keywords

Rice · Stochastic frontier production · Technical and allocative efficiency · Bangladesh

Abbreviations

AE	Allocative efficiency
BBS	Bangladesh Bureau of Statistics
BDT	Bangladeshi Taka
CD	Cobb-Douglas
DEA	Data envelopment approach
FAO	Food and Agriculture Organization of the United Nations
FOC	First order condition
Ha	Hectare
IGP	Indo-Gangetic Plain
KG	Kilogram
MMT	Million metric tons
MoP	Muriate of potash
OLS	Ordinary Least Square
SFA	Stochastic frontier production approach (SFA)
TE	Technical efficiency
TSP	Triple superphosphate
USA	United States of America

24.1 Introduction

Attaining input use efficiency in producing rice is imperative to ensure food security and sustainable development in the world. Rice is the primary staple food for half of the world population (Zeigler and Barclay 2008). In 2019, worldwide per capita rice consumption was more than 78 kg, and rice supplied daily per capita 528 kcal of dietary energy, which was 18% of the total daily dietary energy intake in the world (2927 kcal) (FAOSTAT 2021a). As the world's population is projected to increase between 8.9–10.7 billion by 2050 than 7.7 billion in 2019 (United Nations 2019), more supply of rice is needed to ensure global food security.

Alarmingly, the yield gain harnessed from the Green Revolution has been declining recently due to soil and environmental degradation from overuse and misuse of agricultural inputs such as fertilizers and pesticides. For example, in 2002, the total agricultural use of urea fertilizer worldwide was 40.4 million metric tons (mmt), which has increased by 46% to 58.8mmt in 2018. Similarly, the agricultural use of pesticides in 1990 was 2.3 mmt, which has increased by 79% to 4.1 mmt in 2018 (FAOSTAT 2021b). However, the annual rice yield growth rate, which was 2.3% during 1962–1990, has reduced to 0.1% during 1991–2019 (FAOSTAT 2021c). As the scope of land expansion for producing more rice is mostly an infeasible option, enhancing input use efficiency to ensure more rice production with the least cost is the best option to ensure food security of the burgeoning population in the world. Improving input use efficiency in rice production can also reduce greenhouse gas emissions from the rice sector. Using primary data collected from the rice farmers in Bangladesh, this chapter examined the factors that influence the input use inefficiency of the rice farmers in Bangladesh.

The analysis of input use efficiency can help understand input misallocation in production systems, such as the excessive use of seed and fertilizer relative to labor. The efficiency measurement method begins with the pioneering work of Farrell (1957), who introduced various types of efficiency, such as technical and allocative efficiency. Technical efficiency (TE) measures the ability of a farm to produce the maximum feasible output from a given amount of inputs (output-oriented measure) or to produce a given level of output using the minimum feasible bundle of inputs (input-oriented measure). In comparison, allocative efficiency (AE) measures the ability of a technically efficient farm to use inputs in proportions that minimize the cost of production given input prices. An analysis of production efficiency thus allows policymakers to find a production system that uses inputs efficiently (least-cost combinations of inputs), which improves the profitability of a farm (Watkins et al. 2014). To estimate efficiency, two approaches have been widely used in the literature: the parametric or stochastic frontier production approach (SFA) (Aigner et al. 1977; Meeusen and van den Broeck 1977; Kumbhakar 1990); and the non-parametric or data envelopment approach (DEA) (Coelli 1995). In this study, we use SFA to estimate the input use efficiency (TE and AE) of Bangladeshi smallholder rice farmers.

In Bangladesh, rice is the primary staple food and a dominant cash crop (Bairagi and Mottaleb 2020; Kumar et al. 2018; Meena et al. 2020). Therefore, the food and nutrition security and the agricultural employment of Bangladesh are highly rice-dependent. For instance, more than two-thirds of 8.6 million hectares (ha) of cropland are entirely under rice cultivation (BBS 2019); nearly one-half of the 164 million people are engaged in rice production, processing, and marketing activities (Bairagi and Mottaleb 2020; Kumar and Meena 2020). Bangladesh is the largest rice-consuming country in the world, with a per capita rice consumption of above 268 kg/year (FAOSTAT 2020). Rice provides about two-thirds of the daily total 2574 kcal per capita energy and more than half of 59.6 grams of protein intake (FAOSTAT 2020). Alarmingly, as the population of Bangladesh has been increasing at a 2.11% growth rate per annum from 1961 to 2017, it is imperative to supply more rice to ensure the country's food security. However, the question remains about how to produce more rice to meet the growing demand.

Located in the eastern Indo-Gangetic Plain (IGP), Bangladesh is one of the most densely populated countries in the world, with 1103 persons per square kilometer (Government of Bangladesh 2019). The country is 147,570 km^2 (Government of Bangladesh 2019), which is even smaller in size than the state of Georgia (153,910 kmi^2, USA Census Bureau 2018) in the United States of America (USA). Because of the mounting population pressure, the average farm size in the country has shrunk to 0.68 ha (Quasem 2011). Importantly, the availability of arable land has declined from 0.17 ha/person in 1961 to 0.05 ha/person in 2016 (World Bank 2020). Internally renewable freshwater also fell from 2069 m^3 per capita in 1962 to 679m^3 in 2014 (World Bank 2020). Additionally, cropping intensity reached 194 (BBS 2018), meaning that every piece of cropland in Bangladesh is cultivated nearly twice in a year. It is, therefore, economically infeasible to increase the land area to produce more rice to meet the growing demand.

Further intensification of rice cultivation by applying more chemical fertilizers and pesticides may not be a feasible option to produce more rice in Bangladesh. The rapid expansion of high-yielding modern rice varieties, fertilizer, and irrigation facilities have significantly contributed to Bangladesh's move from a chronic food shortage to a self-sufficient country (Hossain et al. 1994, 2006; Hossain 2009; Dorosh 2000; Ahmed et al. 2000; Mottaleb et al. 2019). For instance, during 1971–1995, the annual average rice yield was 2.1 metric tons (mt) per hectare (ha), which increased to 3.9 mt/ha during 1996–2017 (FAO 2020). Consequently, total rice (rough, paddy) production increased from 27.1 million metric tons (mmt) in 1990–1992 triennium average to 50.4 mmt in 2015–2017. In 2018, with 56.4 mmt of rice production, Bangladesh was the fourth leading rice-producing country globally (after China, India, and Indonesia) (FAO 2020). Currently, Bangladesh is almost self-sufficient in rice production with some sporadic imports. In 2020, Bangladesh ranked 75 out of 107countries in the Global Hunger Index, moving 27 notches up from its position in 2006 (Wiesmann et al. 2006). However, this tremendous achievement came with high environmental costs. The introduction of high-yielding seeds, misallocation of fertilizer, pesticides, and groundwater extraction for irrigation (Mottaleb et al. 2019) have degraded the ecological balance and soil fertility of Bangladesh (Ali et al. 1997; Quamruzzzaman 2006). Declining soil fertility has already started taking a toll: during 1998–2007, the annual growth rate of rice yield in Bangladesh was 4.1%, which declined to 1.4% during 2008–2018 (FAO 2020).

With this backdrop, enhancing rice production efficiency by achieving higher input use efficiency could be an option to produce more rice to ensure the food security of the burgeoning population while minimizing environmental costs. Using primary data collected from 998 farmers in northwest Bangladesh, this study econometrically estimates input use inefficiencies for rice production in Bangladesh. Applying the primal system estimation procedure proposed by Kumbhakar and Wang (2006), this study revealed that the average technical inefficiency in rice production in Bangladesh is approximately 29%, which means that nearly one-third of rice production is foregone. This study identified that the main drivers of this technical inefficiency were not adopting the stress-tolerant rice and not applying pesticides. The results also indicate that the technical inefficiency alone increases the input demand and costs by approximately 5.0%, on average. Input allocative efficiency led to an under-use of seed and fertilizer relative to labor, which increased the actual cost by 6.3%. This suggests that the rice sector in Bangladesh is still a labor-intensive industry. The findings of this study are similar to numerous previous studies, which indicated that input technical efficiencies of different varieties of rice productions range from 16% to 95% (Coelli et al. 2002; Bäckman et al. 2011; Mishra et al. 2015; Afrin et al. 2017b; Gautam and Ahmed 2019; Bairagi and Mottaleb 2020).

The remainder of the chapter is structured as follows: The next section provides a literature review on the production efficiency of rice farms in Bangladesh. Section 24.3 describes the model specification and estimation technique. Details of the data collection and descriptive statistics are provided in Sect. 24.4. Section 24.5 presents the findings and discussion, and finally, Sect. 24.6 concludes with policy implications.

24.2 Rice Production Efficiency in Bangladesh: A Review

The tripling of rice production in the past few decades in Bangladesh was primarily due to technological progress (Hossain et al. 2006; Alam et al. 2011; Azad and Rahman 2017; Gautam and Ahmed 2019). However, the misallocation of production inputs, including seed, fertilizer, and pesticides, are still a concern (Coelli et al. 2002; Bäckman et al. 2011; Majumder et al. 2016), as this can increase production costs and decrease the profitability of rice production. Recent evidence suggests that a higher degree of input use leads to inefficiencies, mainly due to the over-use of seed during the flood seasons, as flash floods often damage seedbeds and growing rice (Hossain et al. 2006). Moreover, streams and run-off water from rain and floods also reduce the effectiveness of fertilizer. The overuse of labor input could also increase rice production costs, as large-scale automation or mechanization has not happened due to small farm sizes (Gautam and Ahmed 2019). Therefore, minimizing the use of inputs will result in substantial gains in rice production with existing technologies and available resources.

Several studies empirically investigated the TE of rice farmers in Bangladesh, which found high variability in the inefficiency of rice farmers (Fig. 24.1). For example, recently (Bairagi and Mottaleb 2020) estimated the average TE of smallholder rice farmers in northwest Bangladesh to be around 66%, suggesting that more than 34% of rice can be produced with the existing levels of inputs. The authors also noted that farmers who participated in an organization were more efficient than farmers who did not. Using a 62-village panel survey (2000–2008) from rural households in Bangladesh, Gautam and Ahmed (2019) estimated the mean TE to be approximately 75%. This indicates that about one-fourth of rice production in Bangladesh is foregone. The author also noted a negative association between farm size and technical inefficiency. Mishra et al. (2015) estimated the TE

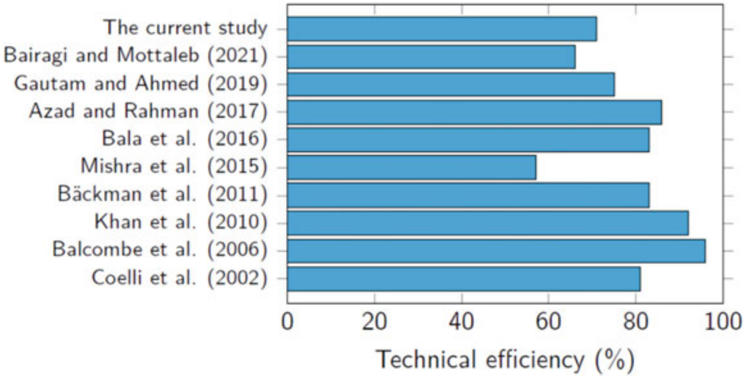

Fig. 24.1 A review of rice production efficiency in Bangladesh

of rice farmers in Bangladesh, ranging from about 16% to 82%, with an average TE of 57%. The authors found that floods caused by excessive rainfall and extreme temperatures are the primary contributors to the inefficiency. Similar variability in TE is also observed by Bäckman et al. (2011), who found TEs ranging between 16–94%, although they did find a higher mean of TE (83%). Bäckman et al. (2011) found the major determinants of inefficiency were: education, off-farm incomes, land fragmentation, access to credit, and extension visits. Access to credit was found to be a crucial contributor to the technical efficiency of paddy farmers in Khulna district of Bangladesh (Afrin et al. 2017b; Kumar et al. 2021). Finally, using the plot level information of 180 farmers from four districts (Jashore, Barishal, Pabna, and Magura) in Bangladesh, Azad, and Rahman (2017) calculated the mean TE of the hybrid rice producers is at 0.86 with a range of 0.55 to 0.97.Concerning the allocative efficiency (AE),we found only one study on rice production in Bangladesh (Coelli et al. 2002), which was conducted two decades ago. The authors estimated that the average AE of *boro* rice farmers in Bangladesh was 81%, which was attributable to overuse of fertilizer and labor. They also found that farmers who had better access to input markets were more efficient compared to their counterparts.

From the above discussion, we can understand the substantial rice production losses in Bangladesh due to technical and allocative inefficiencies. Notably, a considerable variation is found in the estimates of inefficiencies (Fig. 24.1), which could be because of seed varieties, location-specificity (farmers in one area could be more efficient than other areas), and the methods and time used to estimate inefficiencies. Most of the studies mentioned above also estimated TE from the production function approach. Based on this perspective, our study contributes to the literature by assessing both the TE and AE of rice farmers in Bangladesh, utilizing the primal system approach (Kumbhakar and Wang 2006). We hypothesize that input-use inefficiencies can be reduced with location-specific policies, including adopting climate-resilient rice varieties and fertilizer use guidelines (Dar et al. 2013; Bairagi et al. 2020, 2021; Veettil et al. 2020). As a result, the overall rice production cost can be reduced, resulting in increased profitability. The study will provide insights to the policymakers to design appropriate policies, which will help reduce input use inefficiencies for rice production in Bangladesh.

24.3 Method to Estimate Input Use Efficiency of Rice Farmers in Bangladesh

We use the primal system approach proposed by Kumbhakar and Wang (2006) to assess the input use inefficiencies for smallholder rice farmers in Bangladesh. Although the cost-system approach (first introduced by Schmidt and Lovell (1979, 1980) can be used to estimate technical and allocative inefficiencies jointly in a cost-minimizing framework, it has several drawbacks. For instance, it is challenging to link allocative inefficiency in the share and cost equations. It is also difficult to estimate both technical and allocative inefficiency when both inefficiencies are random.

Therefore, we use the primal system approach that first solves the production system for input quantities, and then the results are used to compute the impact of technical and allocative efficiencies on cost. Below we briefly present the primal system that includes the production function and the first-order conditions (FOCs) of a cost minimization problem.

The Cobb–Douglas (CD) production function for a typical producer, *i* (the subscript *i* is omitted due to simplicity) can be expressed as

$$\ln y = \alpha_0 + \sum_j \alpha_j \ln x_j + v - u \tag{24.1}$$

The FOCs for the CD function are

$$\ln\left(\alpha_j/\alpha_1\right) - \ln\left(w_j/w_j\right) - \ln x_j + \ln x_1 = \xi_j \tag{24.2}$$

The first equation is proposed by Aigner et al. (1977) and Meeusen and van den Broeck (1977), where y is the output (rice production in kilogram per hectare, in our case), x is the vector of inputs (seed, fertilizer, and labor, in our case), v is the production uncertainty and u is output-oriented (OO) technical inefficiency, which reveals the percentage of output loss due to technical inefficiency, keeping everything else constant. In Eq. (24.2), w_j is the input prices, where $j = 2, \ldots\ldots, J$; $w_j^s = w_j e^{\xi_j}$ and $\xi_j(\neq 0)$ is the allocative inefficiency for the input pair $(j, 1)$, for example, if $\xi_2 < 0\left(=> w_2 e^{\xi_2} < w_2\right)$ then input x_2 is over-used relative to input x_1.

To estimate Eqs. (24.1) and (24.2), these assumptions of the error structure of equations are made: v and u are half-normal, which are standard assumptions in the efficiency literature; ξ_j is normally distributed as it can be negative and positive, implying that inputs can be over- or under-used; and, for simplicity, it is assumed that u and ξ_j are independent. Mathematically (Eq. 24.3a–d), these distributional assumptions can be written as:

$$v \sim N\left(0, \sigma_v^2\right), \tag{24.3a}$$

$$\mathrm{u} \sim \mathrm{N}^{+}\left(0, \sigma_{\mathrm{u}}^2\right), \tag{24.3b}$$

$$\xi \sim \mathrm{MVN}\left(0, \sum\right), \tag{24.3c}$$

$$\xi_{\mathrm{j}}\text{are independent of v and u} \tag{24.3d}$$

Considering these above distributional assumptions (24.3a)–(24.3d), the joint probability distribution of $v - u$ and $\boldsymbol{\xi}$ can be written as $f(v - u, \boldsymbol{\xi}) = g(v - u).h(\boldsymbol{\xi})$, where $g(v-u) = \frac{2}{\sigma}\phi\left\{\frac{v-u}{\sigma}\right\}\boldsymbol{\phi}\left\{\frac{-(v-u)\sigma_u}{\sigma_v\sigma}\right\}$; ϕ and $\boldsymbol{\phi}$ are respectively the probability density function (PDF) and cumulative distribution function (CDF); $\sigma = \sqrt{\sigma_u^2 + \sigma_v^2}$; $h(\boldsymbol{\xi})$ is the multivariate normal PDF for $\boldsymbol{\xi}$. Therefore, the likelihood function for the primal system (1–2) is written as:

$$L = g(v-u).h(\boldsymbol{\xi}).|J| \tag{24.4}$$

where $|J|$ is the determinant of the Jacobian matrix $|J| = \left|\partial\left(\frac{v-u, \xi_2, \xi_3, \ldots\ldots, \xi_j)}{\partial\left(\ln x_1, \ln x_2, \ldots\ldots, \ln x_j\right|}\right.\right.$, which is required as inputs (x) are endogenous under the assumption of the cost minimization problem. Parameters can then be estimated, maximizing the above log-likelihood function (Eq. 24.4). After estimating the parameters, observation-specific technical inefficiency (u) and input allocative inefficiency ($\boldsymbol{\xi}$) can be computed.

Following the Jondrow et al. (1982) formula, we estimate the observation specific OO technical inefficiency as

$$E[u|(v-u)] = \mu^* + \sigma^* \frac{\phi\left(\frac{\mu^*}{\sigma^*}\right)}{\boldsymbol{\phi}\left(\frac{\mu^*}{\sigma^*}\right)} \tag{24.5}$$

where $\mu^* = -(v-u)\sigma_u^2/\sigma^2$ and $\sigma^* = \sigma_u\sigma_v/\sigma$.

Finally, following Kumbhakar and Wang (2006) the computation technique of estimating cost function with and without inefficiency, we estimate the impact of technical and allocative efficiencies on cost as

$$\ln c^a = a_0 + \frac{1}{r}\ln y + \frac{1}{r}\sum_{j=1}^{J}\alpha_j \ln w_j - \frac{1}{r}(v-u) + E - \ln r \tag{24.6}$$

where $a_0 = \ln r - \frac{\alpha_0}{r} - \frac{1}{r}\left(\sum_{j=1}^{J}\alpha_j \ln \alpha_j\right)$, and $E = \frac{1}{r}\sum_{j=2}^{J}\alpha_j\xi_j + \ln\left[\alpha_1 + \sum_{j=2}^{J}\alpha_j e^{-\xi_j}\right] - \ln r$, and $r\left(= \sum_{j=1}^{J}\alpha_j\right)$ is the returns to scale. The difference between with and without the inefficiency of eq. 6 is $\ln c^{a}|_{u} - \ln c^{a}|_{u=0} \equiv \eta = u/r$. This implies that with a higher r the cost will be lower, ceteris paribus. To estimate the above equations, we use the STATA codes provided by Kumbhakar et al. (2014). The detailed model and estimation procedures are referred to Kumbhakar and Wang (2006) and Kumbhakar et al. (2014).

24.4 Data and Descriptive Statistics

The study used household survey data collected from the Rangpur and Mymensingh regions (Lalmonirhat, Kurigram, Rangpur, Gaibandha, Jamalpur, and Sherpur districts) of northwest Bangladesh in 2016 (Fig. 24.2).[1] A multistage stratified random sampling technique was employed to select the primary sample unit. Firstly, each district mentioned above was divided into two strata, flood-prone and not flood-prone, based on historical flood information from the Bangladesh Bureau of Statistics (BBS), making 12 sub-districts. Secondly, five local administrative units from each sub-district were selected, which are called Unions. From each Union, several villages were randomly selected. Twenty-five rice farmers were randomly selected and interviewed from each village with a structured questionnaire. Finally, a total of 1500 farmers were interviewed face-to-face; however, excluding samples featured missing information and outliers, we ultimately used 998 samples in this study.

Even though the survey questionnaire contained several modules, including farmers' socio-demographic profiles, household characteristics, and the cost and revenue of rice production, we used the following variables: rice production, quantities and prices of inputs (seed, fertilizer, and labor), and inefficiency variables related to rice production (pesticides use, irrigation application, adoption of submergence-tolerant rice varieties, and location specificities).

Table 24.1 reveals the descriptive statistics of the model variables. The average yield rate of Aman rice (rough) in the study area was about 3.70 mt/ha. However, there is high variability in the yield rate, with a standard deviation of 1.25 mt/ha. Regarding the use of production inputs, approximately 44 kg of rice seeds, 296 kg of fertilizers (urea, TSP, and MoP), and 78 person-days of labor were used per ha. These input use rates are consistent rates in Bangladesh (Bairagi et al. 2021; Bairagi and Mottaleb 2020). The reported input prices were 44 Bangladeshi Taka (BDT) per kg of seeds and BDT 60 per kg of fertilizer. The wages of BDT 288 per person-day were also consistent with the market prices. Table 24.1 also reveals that two-thirds of the sampled farmers applied pesticides, and irrigated water was used by one-half of the farmers. Approximately 42% of the surveyed farmers in the study areas had adopted any type of climate-resilient rice variety, such as submergence-tolerant varieties. Finally, approximately 60% of the samples were collected from the greater Rangpur district.

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[1] We thank the International Rice Research Institute (IRRI), Dhaka Office, for sharing this data.

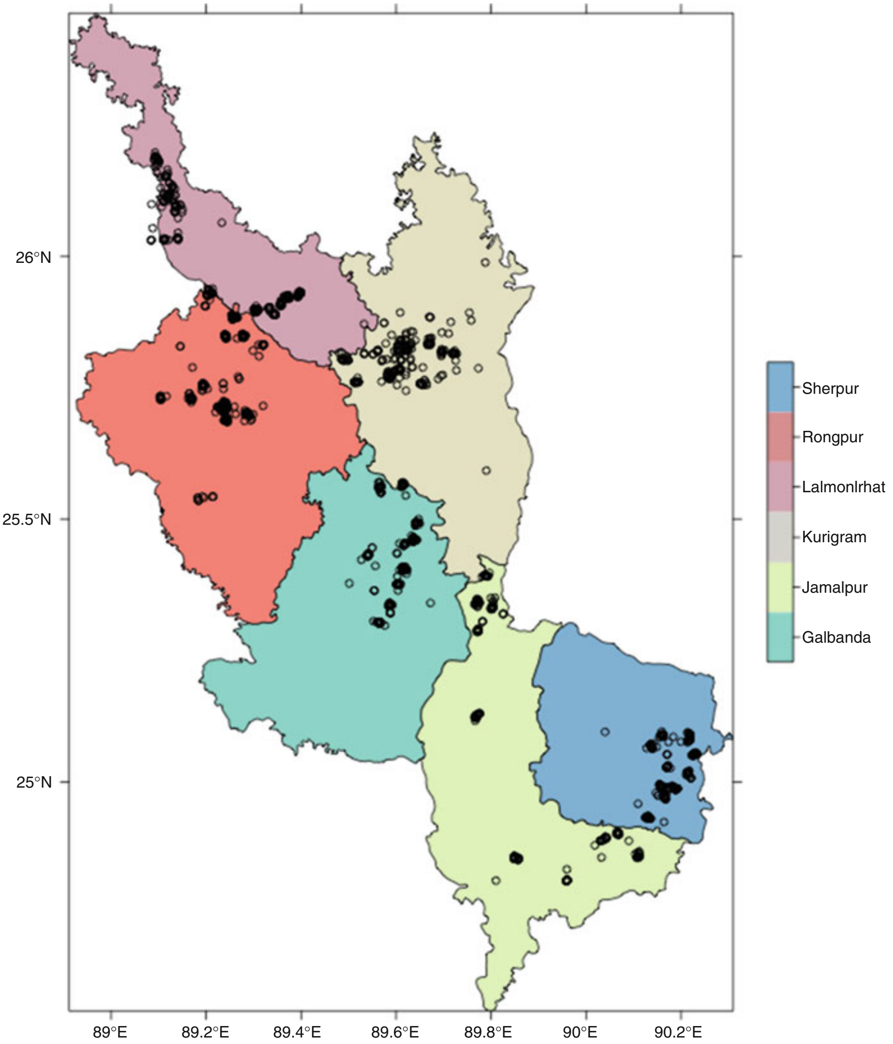

Fig. 24.2 Study Areas in Northwest Bangladesh. Notes: Prepared by Authors Based on Survey Data. Black Dotted Points are the Sampled Farmers

24.5 Input Use Inefficiencies in Rice Production in Bangladesh

Table 24.2 presents the estimated parameters from the stochastic frontier (SF) production function (Eq. 24.1). We use three production inputs, of which fertilizer and hired labor are statistically significant at the 1% level, which is as expected. Since we use a log-log form, the coefficients of production functions are elasticities. The elasticity of output with regard to fertilizer and labor are estimated at

Table 24.1 Descriptive Statistics for the Variables Used in the Econometric Analysis

Variables	Description	Mean	Standard deviation
Production variables			
Rice yield	Rice production in kilogram (kg) per hectare (ha)	3694.24	1250.36
Seed	The total quantity of seed used, kg/ha	44.31	35.48
Fertilizer	The total quantity of urea, MoP (Muriate of potash), and TSP (triple superphosphate) used, kg/ha	295.96	84.80
Labor	Total labor used, person-days/ha	78.41	37.82
Prices			
Seed price	Price of seed, BDT/kg	43.56	13.65
Fertilizer price	The mean price of urea, MoP, and TSP, BDT/kg	60.25	7.70
Labor price	Price of hired labor (wage), BDT/person-day	288.08	55.19
Inefficiency variables			
Pesticide	1 = if farmers used pesticides, 0 otherwise	0.73	0.44
Irrigation	1 = if farmers applied irrigation, 0 otherwise	0.54	0.50
Flood-resistant varieties	1 = if farmers adopted any of submergence-tolerant rice varieties, 0 otherwise	0.42	0.49
Location	1 = greater Rangpur district, 0 greater Mymensingh district	0.63	0.48
Observations		998	

Notes: Authors' computation. BDT stands for Bangladesh's currency in Taka

0.12 and 0.10, which are consistent with previous studies in Bangladesh (Hossain et al. 2006; Bäckman et al. 2011; Afrin et al. 2017b). Regarding the presence or absence of technical inefficiency, we perform a statistical test with the log-likelihood values of the restricted ordinary least square (OLS) and the unrestricted SF model, which is $LR = -2 * L(H_{ols} - H_{sf})$. The LR test statistic is significant at the 1% level, suggesting the presence of production inefficiency for rice farmers. We find the main drivers of rice production inefficiency are not applying pesticide and not adopting submergence-tolerant rice varieties (bottom section of Table 24.2), which are elaborated below.

The coefficient of adoption of submergence-tolerant (Sub1) rice varieties is negative and significant at the 5% level (Table 24.2), meaning that farmers who used Sub1 rice seeds are more efficient than farmers who did not. This finding is consistent with a recent study that evaluated the impacts of the adoption of Sub1 rice varieties in northwest Bangladesh (Bairagi et al. 2021): farmers who adopted Sub1 rice used fewer inputs and achieved greater yield, and consequently made a significantly higher profit than non-adopters. This could be one of the main reasons for the ease of spread of Sub1 rice varieties among the neighbors of early adopters, who realized the benefits of Sub1 rice (Yamano et al. 2018). Nonetheless, although Sub1 rice has no yield penalty under normal conditions, the adoption rate of Sub1 rice is still low in Bangladesh (Yamano et al. 2018; Bairagi et al. 2021). Therefore, we

Table 24.2 Estimated production function parameters (Eq. 24.1)

Exogenous variables	Production frontier model
Production variables	
Constant	7.535***(0.19)
Seed (kg/ha), log	−0.006(0.01)
Fertilizer (kg/ha), log	0.119***(0.03)
Hired labor (person-days/ha), log	0.101***(0.02)
Inefficiency variables	
Constant	−0.811***(0.13)
Pesticide used (yes = 1)	−0.270**(0.11)
Irrigation application (yes = 1)	0.015(0.10)
Adoption of submergence-tolerant rice varieties (yes = 1)	−0.248**(0.10)
Location (greater Rangpur district = 1) (base: Greater Mymensingh district)	0.119(0.10)
σ_v^2	0.013*** (0.002)
LR test statistics	210.65***
Wald chi squared	46.46***
Log-likelihood	−360.86
Observations	998

Notes: Significance: ***: 1% level; **: 5% level; *: 10% level. Figures are in parentheses are standard errors

suggest scaling out of Sub1 rice by educating farmers about the technology, disseminating Sub1 seeds, and incentivizing farmers to adapt Sub1 rice varieties, particularly in flood-prone zones in Bangladesh.

The coefficient related to pesticide use (yes = 1) is negatively and significantly correlated with technical inefficiency. This suggests that farmers who used pesticides are comparatively less inefficient (or more efficient) than their counterparts who did not use pesticides. This finding is consistent with Robinson et al. (2007), who noted that pesticides use in rice farming systems in Bangladesh is comparatively lower than in Southeast Asian countries. In contrast, our finding is somewhat contrary to studies that pointed to the over-use of pesticides in Bangladesh (Dasgupta et al. 2007; Afrin et al. 2017a). However, pesticide use is likely to vary by crop (cereals vs. vegetables) and rice types (Aman vs. *boro* rice). Dasgupta et al. (2007) found that Bangladeshi farmers who produce a significant proportion of rice than the other crops they are growing are 40–90% less likely to overuse pesticides. The over-use of pesticides could be location-specific (Robinson et al. 2007). Since we study the production performance of Aman rice in northwest Bangladesh, the optimal use of pesticides can increase production performance in those specific areas. However, we suggest educating farmers about pesticide use, its environmental effects, and the use of alternative methods (e.g., Integrated Pest Management) through training and extension services in order to achieve higher levels of rice production with the current levels of inputs.

24.6 Impact of Technical and Allocative Inefficiencies

Table 24.3 presents the inefficiency-induced reduction in rice production and an increase in cost, estimated from the model by Kumbhakar and Wang (2006). The data and STATA codes are freely accessible in Bairagi (2020). The results show that the mean output-oriented technical inefficiency is approximately 29.1%, meaning that about 29% of more rice can be produced given the input bundles currently being used. Therefore, there is enormous scope available to reduce the production inefficiency of rice farmers, particularly by disseminating climate-resilient rice varieties, such as submergence-tolerant (Sub1) rice varieties (Mishra et al. 2015; Yamano et al. 2018; Bairagi et al. 2021). As is shown in Fig. 24.3, rice farmers who adopted Sub1 had significantly lower production inefficiencies compared to the farmers that did not. Finally, our estimate of technical inefficiency is consistent with previous studies of Bangladesh (Mishra et al. 2015; Gautam and Ahmed 2019; Fig. 24.1).

Table 24.3 also presents the cost of rice production increases due to technical and allocative inefficiencies. We find that the cost of rice production due to technical inefficiency is increased by 5.0% on average, whereas allocative inefficiency raises costs by 6.3% (rows 2–3, Table 24.3). A plausible explanation is that the rice sector is still a labor-intensive industry in Bangladesh.

We also estimate input allocative inefficiency, ξ, for seed and fertilizer relative to labor. The mean value of ξ_S and ξ_F are positive (0.085 and 0.094, respectively) (rows 4–5 of Table 24.3). This result indicates that, on average, labor/seed and labor/fertilizer ratios are higher than the cost-minimizing ratios. In other words, both seed and fertilizer are under used relative to labor in Bangladesh. This is consistent with the fact that rice production in Bangladesh is still a labor-intensive enterprise. Therefore, enhancing mechanization can reduce the cost of rice production, originating from allocative inefficiencies.

24.7 Conclusions and Policy Implications

In this study, we estimated the input use inefficiencies for rice production in northwest Bangladesh. We utilized the primal system of stochastic frontier (SF) model, using information from 998 farmers that produce Aman rice. The

Table 24.3 Impact of technical and allocative efficiencies on rice production and cost

Components		Mean	Standard deviation
Rice production inefficiency (technical)	$E_{\widehat{u}}$	0.291	0.185
Cost inefficiency (technical and allocative)		0.115	0.086
Increase in cost due to technical inefficiency	C^{tech}	0.050	0.032
Increase in cost due to allocative inefficiency	C^{alloc}	0.063	0.078
Allocative inefficiency for seed relative to labor	$\widehat{\xi}_S$	0.085	0.900
Allocative inefficiency for fertilizer relative to labor	$\widehat{\xi}_F$	0.094	0.636

Notes: Estimated with the primal system with no systematic errors in allocation

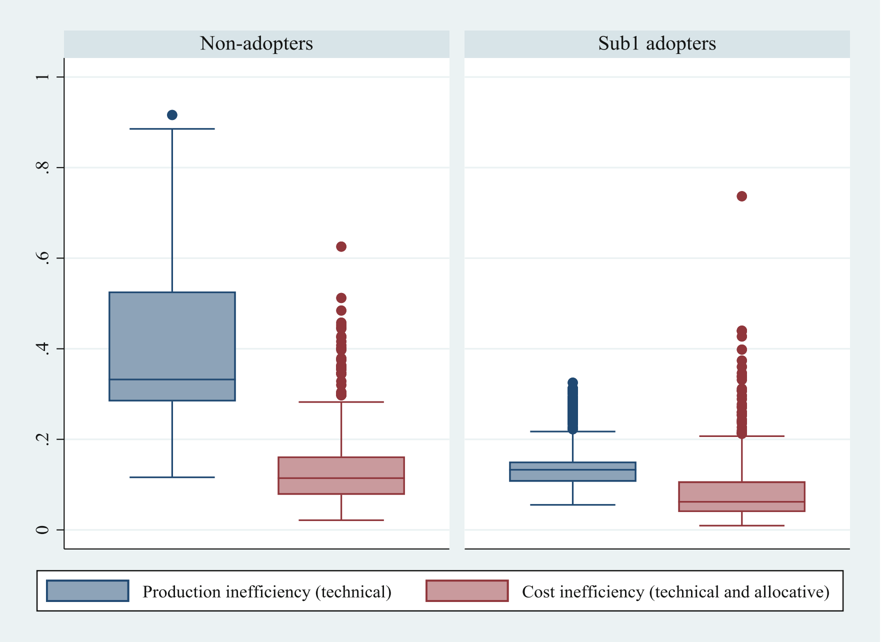

Fig. 24.3 Technical and allocative inefficiency by the adoption of submergence-tolerant (Sub1) rice varieties

findings reveal that the average technical inefficiency is approximately 29%, which indicates that one-third of rice production is foregone. In other words, on average, a farmer in Bangladesh can produce 29% more rice with the current input bundles. The main drivers of technical efficiency are the adoption of submergence-tolerant (Sub1) rice varieties and pesticides application. This means that farmers who adopted Sub1 rice and applied pesticides are more efficient compared to their counterparts that did not adopt Sub1 rice and use pesticides. Therefore, there is enormous scope to reduce the production inefficiency of rice farmers in Bangladesh, particularly by disseminating climate-resilient rice varieties, such as Sub1 rice varieties (Mishra et al. 2015; Yamano et al. 2018; Bairagi et al. 2021; Yadav et al. 2020), and by educating farmers about pesticide use based on the standard fertilizer recommendation guidelines. Furthermore, findings suggest that the input demand and costs increased by approximately 5.0% as a result of technical inefficiency alone. Input allocative efficiency led to an under-use of seed and fertilizer relative to labor, which increases the actual cost by 6.3%. Therefore, we suggest enhancing scale-appropriate mechanization for various farming activities, such as weeding and harvesting, to reduce the cost of rice production in Bangladesh.

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