Amitava Rakshit
S. K. Singh
P. C. Abhilash
Asim Biswas *Editors*

Soil Science: Fundamentals to Recent Advances

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To our parents for their unbiased support

Preface

Human society has developed through utilization of our planet's wealth in incredibly exclusive, inventive, and prolific ways that have advanced human advancement and sustained global societies. Of these resources, soil is the most important economic industry that has provided humans with the ability to produce food, through agriculture, for our sustenance. It also plays an integral role in countless other ecosystem services like water and climate regulation. In exploring the link between soil and agriculture, we have moved through phases like transition from hunter-gatherer to agrarian societies, major soil properties that contribute to fertility, intensive agriculture impact on soil degradation, and the basic concepts of sustainable agriculture and soil management. All through human history, our association with the soil has affected our aptitude to cultivate crops and influenced the accomplishment of civilizations. This rapport between humans, the earth, and food sources affirms soil as the foundation of agriculture. Soils are important for human health in a number of ways. Approximately 80% of the average per capita calorie consumption worldwide comes from crops grown directly in soil, and another nearly 20% comes from terrestrial food sources that rely indirectly on soil. Soils are also a major source of nutrients, and they act as natural filters to remove contaminants from water. However, soils may contain heavy metals, chemicals, or pathogens that have the potential to negatively impact human health. In the present context, soil science has to play a more serious role to its stakeholders in times to come. It is high time to get rid of over-generalizing recommendations beyond the conditions for which they were developed. There is an urgent need to communicate the risks inherent in the recommendations and finally findings need to be translated into economic terms so that farmers and policy-makers can work with them.

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S. K. Singh received his B.Sc.(Ag) degree in 1985 and M.Sc.(Ag) in 1988 and Ph.D. in Soil Science and Agricultural Chemistry in 1992 from Banaras Hindu University, Varanasi. He started his professional career in 1990 as Lecturer of Agricultural Chemistry in Amar Singh (PG) College, Lakhaoti, Bulandshahr subsequently Dr Singh joined as Associate Professor in the year 1999 at G.B. Pant University of Agriculture and

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Asim Biswas is an Associate Professor at the School of Environmental Science, University of Guelph, Canada. He is also an Adjunct Professor at the Department of Natural Resources Sciences, McGill University Canada, a Visiting Professor at Jiangxi University of Finance and Economics and Jiangsu University, China. His research program on sustainable soil management is focused on increasing the productivity and resilience of our land-based agri-food production systems in an environmentally sustainable way while accounting for changing climate, economy, and production methodologies. Currently, he runs a 21-member research team, funded by federal and provincial bodies as well as industries, grower's associations, and international organizations. He has authored and co-authored 113 peer-reviewed journal papers including 21 in review, 165 conference abstracts, 12 proceedings, 15 book chapters, 2 popular articles, edited a book, delivered radio and TV interviews, and granted a patent. He was invited to deliver keynote talks around the world and currently teaches multiple undergraduate, graduate, and special courses. Currently, he is an Associate Editor for 4 journals and a guest editor for another 4 journals.

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Part I

General Concepts and Development

Managing Soil Resources for Human Health and Environmental Sustainability

1

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Abstract

Rapidly increasing global human population has led to the intensive land use change, and the over exploitation of soil resources resulting in the diminished soil health, ecosystem services, and human well-being. Depriving nutrients from the soil systems due unsustainable practices has further led to low productivity and quality of the crop yields. As a result, it led to the scarcity of the food with limiting nutrients reflecting various nutrient deficiencies and human health disorders. Therefore, it is the need of the hour to restore the health of our soil resources for improving the food and nutrition secuirty of present as well as future generations. In this backdrop, the present chapter is aimed to discuss the drivers of soil degradation, highlight the impact of soil degradation on human health and suggests various adaptive practices to maintain the soil health while improving the quality of crop yield for environmental sustainability and human health.

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Keywords

Soil degradation · Soil health · Adaptive management · Sustainable development · Human health

1.1 Introduction

Soil is one of the important life-supporting resources of the planet earth. It not only provides food, fodder, fuel, and fiber but also regulates the quality of air and water (Rakshit et al. 2017; Tripathi et al. 2017). However, the increasing anthropogenic activities coupled with unsustainable soil management practices lead to desertification, pollution, reduced biodiversity, and organic matter content (Tripathi et al. 2014). The low nutrient status in soil has resulted in decreased productivity and nutrients in crops, thereby negatively affecting the good health and human well-being (IPBES 2018). It has been estimated that around 33% of the global soil resources are in a state of degradation, affecting the livelihoods of billions (Wall and Six 2015; IPBES 2018). As the rapidly increasing human population require 50–70% increase in the production of food, fiber, and fodder in the near future, the arable land requirement for meeting such demand is about 2.7–4.9 M ha y^{-1} (Lambin and Meyfroidt 2011; Abhilash et al. 2016). While soil fertility is replenishable up to a certain extent, it will take hundreds of years to regain the vitality of the soil to maintain the critical soil ecosystem functions and services. In this backdrop, the sustainable management of the global soil resources is imperative to meet the food and nutritional security of the growing population while maintaining the soil fertility, productivity and soil ecosystem services for meeting the UN-Sustainable Development Goals (Dubey et al. 2016; Edrisi and Abhilash 2016; Sarkar et al. 2020). Considering the importance of soil resources for sustainable agriculture and human health and thereby creating a global solidary for the conservation and management of soil, United Nations has declared the period of 2015–2024 as International Decade of Soil, whereas the decade 2021–2030 as the International Decade of Ecosystem Restoration. Moreover, a lot of international efforts are underway to increase the awareness about the sustainable management of global soil resources (Lambin and Meyfroidt 2011; Edrisi et al. 2019) and restoring the already degraded soil to regain the fertility and ecosystem functions for a good quality of human life (IRP 2019). The present article briefly discusses various drivers of soil degradation, the impact of soil quality degradation on crop production as well as human health and propose suitable management practices for maintaining the vitality of soil.

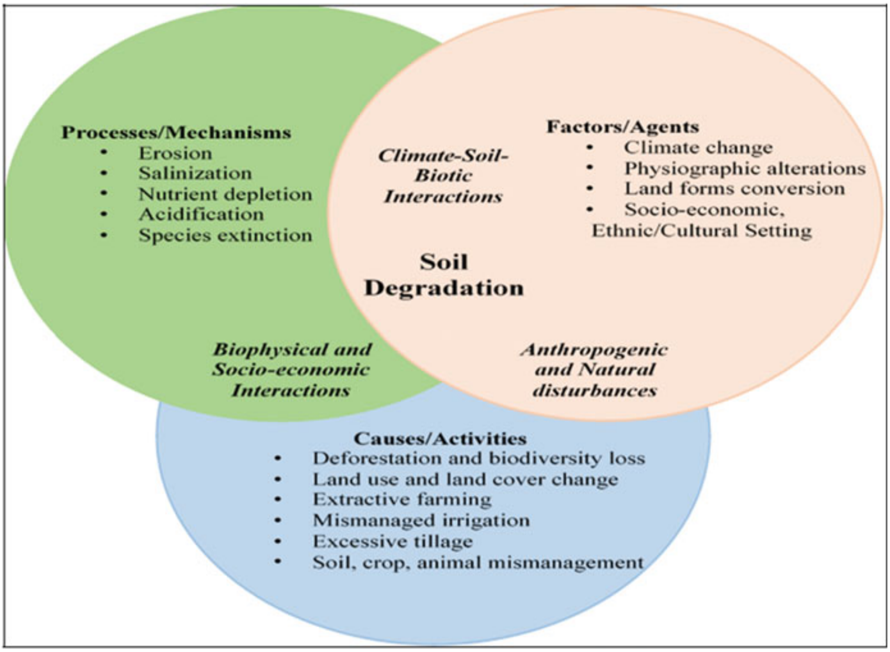

Fig. 1.1 The nexus of different processes, factors, and causes as major indicators of soil degradation (adapted from Lal 2015; IPBES 2018)

1.2 Drivers of Soil Degradation

As mentioned in Fig. 1.1, there are several interconnected factors affecting the degradation of the soil resources such as (1) climate–soil–biotic interactions, (2) biophysical and socio-economic interactions, and (3) the anthropogenic and natural disturbances (Fig. 1.1). Periodic monitoring of these interactions is required to understand the behavior of various drivers on soil ecosystem functions and services and also for the implementation of efficient restoration and management approaches (Tripathi et al. 2014; Edrisi et al. 2019).

1.3 Soil Degradation and Human Health

Quality of soil is directly related to malnutrition and basic public health issues (McMichael et al. 2007). Accordingly, the degradation of soil quality directly and indirectly affects the human nutrition and health because of the fact that soil quality degradation decreases both the quantity and quality of the agricultural produce (IRP 2019).

Therefore, reduced crop yield has resulted in global food scarcity which in turn affects over 854 million peoples across the world. Moreover, the reduced concentration of proteins and micronutrients (Zn, Se, Fe, I, etc.) leads to malnutrition and hidden hunger affecting 3.7 billion population, particularly the children (Lal 2009). In addition to the insufficient calorie intake, micronutrient deficiencies are the common reason for mortality (Black 2003; Ezzati et al. 2002), and especially, children are more susceptible to Zn (Sazawal et al. 2001) and vitamin A (Humphrey et al. 1992) deficiencies. For instance, half of the mortality rate of children under the age of five in India are mainly due to under nutrition (data.unicef.org).

Similarly, around 24% of all children in China are victims of Fe deficiency, while over 50% suffer from of Zn deficiency (Yang et al. 2007). Keshan and Kaschin–Beck diseases occur in regions of soils with lower Se concentration (Yang et al. 2007). With rapid industrialization, soil contamination (e.g., Pb and As pollution) represents severe health concern in China and developing countries like India (Chen 2007; Qi et al. 2007). Brick kilns, in rapidly urbanizing India, consumes annually 1 m of topsoil from 0.5% to 0.7% of cropland area particularly in the northern states of Haryana and Punjab. Food crops grown on shallow soils are deficient in micronutrients. Pimentel et al. (2007) attributed occurrence of several human diseases to air, water, and soil pollution. Following the massive deforestation, hookworm infection has been increased by 12% of the population in Haiti in the year 1990, which further enhanced up to 15% in 1996 (Lilley 1997). Dry land salinity already affecting 1.05 million hectare (Mha) in southwest Australia, and have potential risk of disseminating to 1.7 or even up to 3.4 Mha and has intense human health implications (Jardine et al. 2007).

Hence, there is a close proximity between the mismanaged practices adopted and the depleting soil and human health (Fig. 1.2). This could be either in the form of land use or the overexploitation of such soil resources resulting in the soil erosion and other loss of soil nutrient status, which subsequently leads to the degradation of these natural resources. This rises the scenario of food and nutrient scarcity for the associated peoples, involved labors, and other stakeholders might lead to their retarded or serious health impacts and thereby diminishing their work efficiency (Fig. 1.2).

1.4 Strategies for the Management of Soil Resources

Adaptive management practices can play vital role in combating nutrient depletion managing problem soils, managing soil erosion, and optimizing soil-water use. Adaptive management can be generally defined as an iterative decision-making tool which is both operationally and conceptually a simple aid that incorporates users to acknowledge and account for uncertainty and sustain an operating environment that allows for its reduction through careful planning, evaluation learning until desired results are achieved (Rakshit et al. 2017). It has been reported that various edible crops have also been grown from the polluted lands to serve the burgeoning global population (Ilbas et al. 2012; Meers et al. 2010; Yu et al. 2014; Warren et al.

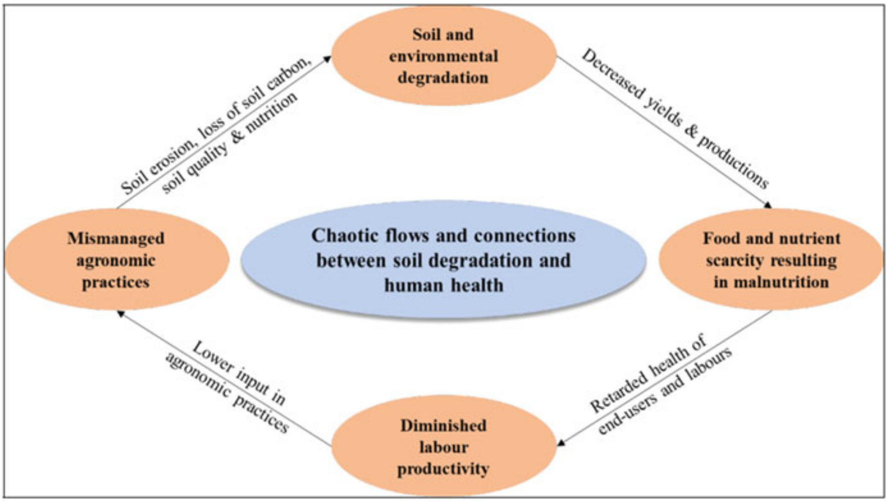

Fig. 1.2 Schematic depiction of soil degradation and human health (modified from Deckelbaum et al. 2006)

2003; Stasinos and Zabetakis 2013). Ilbas et al. (2012) have grown barley in the selenium contaminated field and estimated the Se level to be 0.17 mg kg^{-1}.

Moreover, Meers et al. (2010) have studied the growth of Maize crops in the multi-contaminant polluted land and restricted the Cd, Pb, Zn level in the grains to 0.07 mg kg^{-1}, 0.10 mg kg^{-1}, 0.73 mg kg^{-1}, respectively, which are under the permissible limit as per the FAO standards. Yu et al. (2014) studied the performance of Rice and Rapeseed in the mixed-contaminated sites and observed the levels of Zn (22.8–23.8 mg kg^{-1}) and Cd (0.1 mg kg^{-1}) in the rice and the Cd (0.2 mg kg^{-1}) in the rapeseed, which are under the permissible limit as per the WHO standards. Warren et al. (2003) have also restricted the level of As (<0.08 mg kg^{-1}) in the edible parts of Beetroot grown in the As-contaminated soils in the field. Similarly, Stasinos and Zabetakis (2013) have observed the level of Ni in the carrot, which is estimated to be 0.73 mg kg^{-1} in the Ni contaminated sites. All the aforesaid researches have made use of either the plant growth promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungus (AMF), or other novel plant growth promoting microorganisms (PGPMs) in the consortia which have provided the potentials to those plant species to tolerate such adverse conditions in field. Also the endophytic microorganisms had played a vital role in restricting the pollutant levels to the permissible limit for human intake as dietary supplements.

There are various regional and international initiatives for soil resource management that focused on enhancing the resource use efficiency such as correcting micro and secondary nutrient deficiencies in the soil has shown to increase crop productivity by 20–66% in Karnataka, India (Wani et al. 2017). As a result, five million farmers have been benefitted and has the net economic benefits through enhanced production were estimated to be around US$353 million (1963 crores). Furthermore, the importance of traditional ecological knowledge (TEK) has also been viewed as a pertinent practical solution to the soil restoration and its management (Sharma 2017). Agro-ecosystem management practices, which are the proximate part of the TEK are attracting attention due to its better adaptability and sustainability. Bio-mulching, seed treatments, native seeds and varieties, bioformulations, vermicompost, natural pesticides, livestock rearing are some of the TEKs which has been utilized in different regions of India to uplift the sustainable productions. Semi-arid tropical zone like the region of Kachchh in Gujarat has been employed with these TEKs and found to have better health of soil regarding the phosphorus availability in the soil via phosphate solubilizing microbes (Sharma et al. 2014).

Moreover, the impacts of natural perturbations like forest fire and other changes on soil properties and human environments should also be focused to maintain the viability of such ecosystems (Zhang and Biswas 2017). Adaptive management could play a vital in managing these issues for maintaining the soil carbon pool in the boreal forests. Norris et al. (2009) compared the response of SOC content at 4, 29, and 91 years following disturbance and reported a drastic carbon loss at 4 years after the fire, while gradually rising again over a long period (SOC from 2% after 4 years to 33% after 91 years for forest floors). Apart from the SOC, various other nutrients such as nitrogen, phosphorus, and many base cations like potassium, calcium, etc. are also lost in the forest fire regimes, depleting the soil quality, rising GHG emissions and hence the adverse impact on the human health. To overcome such scenarios, predicting the future forest fires via geospatial technology could play an empirical role (Bui et al. 2019). Also, there is an urgency to monitor the quality of soil health in other ecosystems like urban and riparian systems to devise suitable management actions accordingly.

Since, there is a potential disagreement between the social and ecological goals for the ecosystem restoration (Dudley et al. 2005), hence most of the restoration projects which either ranked the social or economic needs that failed to effectively address broader ecological impacts or focused on narrow mitigation targets without considering the fundamental needs of the people (IRP 2019). It is evident from the past that the indigenous peoples and traditional farmers often developed diverse and adapted agroforestry systems in the vicinity. This resulted in local food security, conserving regional biodiversity and ensued socio-ecological resilience (Altieri 2004; Parrotta et al. 2015; IRP 2019). Such systems can be recognized by studying the possible trade-offs between the benefits of diverse agro-ecosystems and changes in the staple crops production. In order to address these challenges, accounting landscape variability while planning rehabilitation and restoration allows many of the trade-offs for alleviating hunger, while increasing the potential co-benefits (IRP 2019). Such trade-offs can be avoided by providing temporary access to land in another part of the landscape or by intensifying production on one part of the farmer's land while taking another part out of production. Co-benefits can be enhanced by targeting such restoration funds where the most returns are possible.

1.5 Conclusion and Way Forward

Widespread multi-nutrient deficiencies and deteriorating soil health are the causes of low nutrient-use efficiency, productivity, and profitability. Apart from this, the related issues of the climate change have created the enhanced depletion of soil quality, availability of irrigation water and use efficiency of resources and inputs, and crop productivity. The adoption of climate resilient practices along with the application of remote sensing, GIS and advanced restoration technologies are imperative for restoring the fertility of the soil health for sustainable development. This would not only help in combating climate change issues but also help in formulating strong policies for managing soil resources.

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2 Soil Organic Carbon Dynamics, Stabilization, and Environmental Implication

M. C. Manna and Avijit Ghosh

Abstract

Administering soil organic carbon (SOC) has now been acknowledged as the most essential aspect for managing the climate change, soil fertility as well as productivity. Various SOC pools and processes govern the SOC dynamics in varied agro-ecosystems. SOC dynamics in soil is manipulated by management practices, soil type, and climate. Perceptions of the different soil C pools and processes are of imperative significance prior to the execution and success of SOC management. Diverse agro-ecological approaches such as organic and integrated plant nutrition system have been proposed across different agroecologies to achieve a balanced SOC dynamics via suitable agro-management, though accepted with limited eagerness.

Keywords

Soil organic carbon · Carbon dynamics · SOC fractions · Global climate change · Carbon management

2.1 Introduction

Excluding carbonate rocks (inorganic carbon path), the soil represents the largest terrestrial stock of carbon (C), holding 1500 Pg (1 Pg = 10^{15} g), which is approximately twice the amount held in the atmosphere and three times the amount held in

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the terrestrial vegetation. Soil inorganic carbon (SIC) pool contains 750–950 Pg C. Terrestrial vegetation is reported to contain 600 Pg C. Atmospheric concentration of carbon dioxide and other greenhouse gases are changing rapidly because of anthropogenic activities including fossil fuel combustion, deforestation, biomass burning, cement manufacturing, drainage of wetlands, and soil cultivation. The current level of carbon dioxide concentration in the atmosphere (which was at 370 ppm in 2004) is increasing at the rate of 1.5 ppm/year or 3.3 Pg C/year. Researchers predicted that unless necessary measures are taken immediately to reduce net emission of carbon dioxide, it may increase to 800–1000 ppm by the end of twenty-first century. Climatic sensitivity to atmospheric enrichment of carbon dioxide may be 1.5–4.5 °C rise in mean global temperature, with attendant increase in sea level. About 20% of the earth's land area is used for growing crops and thus farming practices have a major influence on C storage in the soil and its release into the atmosphere as CO_2. Within cropping/farming system, the equilibrium levels of soil organic carbon (SOC) can be related linearly to the amount of crop residue returned/applied to soil. The rate of accumulation of SOC depends on the extent to which the soil is already filled by SOC, i.e., the size and capacity of the reservoir. Mechanical disturbance of soil by tillage increases decomposition rate of SOC. Practices, which increase residue and/or plant growth result in enhancing SOC sequestration. The beneficial effect of SOC is more than improving soil quality and fertility.

Total geographical area of India is 328.7 million hectares (m ha) or about 2.5% of the total land area of the world. It is home to 1.1 billion or 16% of the world population. India is the second most populous country in the world. Principal land uses include 161.8 m ha of arable land (11.8% of the world) of which 57.0 m ha (21.3% of the world) is irrigated, 68.5 m ha of forest and woodland (1.6% of the world), 11.05 m ha of permanent pasture (0.3% of the world), and 7.95 m ha of permanent crops (6.0% of the world). The large land base, similar to that of the USA and China or Australia, has a potential to sequester C and enhance productivity while improving environmental quality. The Green Revolution of the 1970s needs to be revisited to enhance production once again and to address environmental issues of the twenty-first century including climate change. Organic carbon in soil play multi-functional role leading to reduction in productivity, enhance input use efficiency (e.g., fertilizer, irrigation), protect pollution of surface and ground water, and minimize emission of greenhouse gases (GHGs) from terrestrial and aquatic ecosystems into the atmosphere and help to improve the soil degradation (Swarup et al. 2000; Manna et al. 2018). Majority of carbon is held in the form of soil organic carbon, having a major influence on soil structure, water holding capacity, cation exchange capacity, etc.

Thus, in this paper, SOC dynamics, total carbon stocks, stabilization mechanism, and environmental quality have been discussed. Further, the C-sequestration mechanism, possible ways to enhance SOC has also been highlighted.

2.2 Soil Organic Pools and Dynamics

So far, literature on soil organic matter (SOM) changes in rainfed, semiarid, and sub-humid regions of India did not throw much light on the carbon functional pools, which are highly sensitive indicator of soil fertility and productivity. The distribution of soil organic matter into the following five functional pools may be made for its true representation (Parton et al. 1987).

Structural Litter Fraction This consists of straw, wood, stems, and related plant parts. The C:N ratio varies around 150:1. These are high in lignin.

Metabolic Pool Fraction It comprises plant leaves, bark, flower, fruits, and animal manure. The C:N ratio ranges from 10 to 25. This fraction contributes mineral nitrogen when it is decomposed.

Active Pool of Soil Carbon This is microbial biomass and their metabolites. The C:N ratio is around 5–15. This fraction contributes mineral nutrients and it gives life to the soil. Besides microbial biomass C (SMBC), light fraction of organic matter, water soluble carbon, and water soluble carbohydrates are also active pools of organic matter.

Slow Decomposable Soil Fraction This fraction is comparable to nature of composting materials having C:N ratio around 20:1. It makes temporary stable humus in soil, which is slowly decomposable.

Passive Soil Organic Fraction This is the highly recalcitrant organic matter with C:N ratio of 7:1 to 9:1. It is resistant to oxidation and is not readily involved in dynamic equilibrium with other types of organic fractions in soil. The specific relationship of management practices and biologically active soil organic matter with soil process is not well characterized. The structure of SOC sub-model is illustrated in century model (Fig. 2.1) (Parton et al. 1987).

This model includes respiratory C losses associated with dynamics of organic pools. Similarly, the N-sub models have the same basic structure of SOM and also include the flow of nutrients in different mineral forms. Moreover, SOC turnover is dependent on soil moisture, radiation, temperature, cropping, rooting, plant residue, etc. Combined effect of all these factors on the dynamics of SOM is not yet established in tropics. Studies therefore, need to be conducted to develop a model of SOM for rainfed cropping systems which will include different parameters such as physical properties of soil, nutrient status, light fraction of SOC, hot water soluble carbon, SMBC, activity of enzymes, etc. Such model may be of great practical importance from management point of view and as an indicator of soil quality.

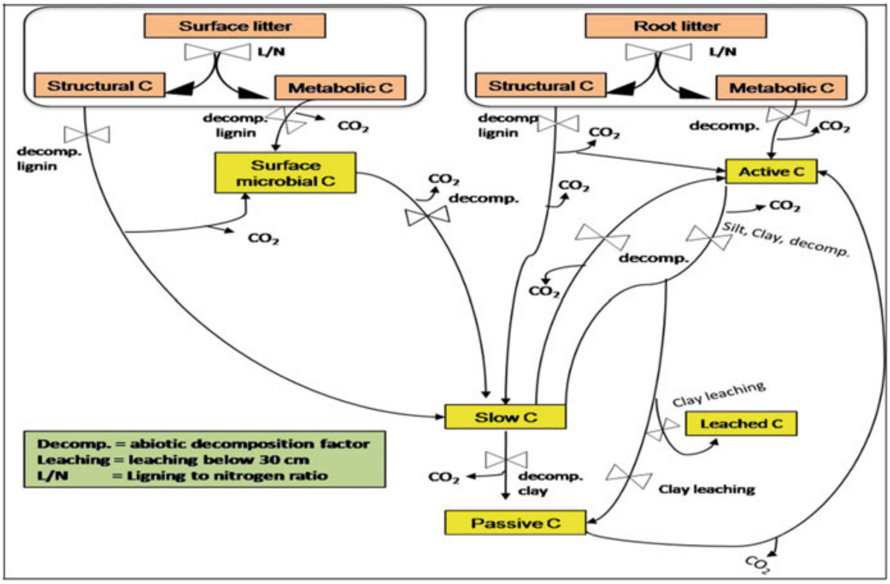

Fig. 2.1 Soil organic pool and dynamics in century model. Source: Parton et al. (1987)

2.3 Long-Term Application of Fertilizer and Manure on Active and Slow Pool of Carbon

Long-term application of NPK and NPK+FYM maintained or improved SOC content over initial values (Bhadoria et al. 2003; Manna et al. 2006; Joshi et al. 2017; Ghosh et al. 2019). Moreover, active fractions of SOC, viz., particulate organic carbon and hydrolysable carbohydrates, soil microbial biomass C and N were improved significantly with the application of NPK and NPK+FYM over control both in case of Alfisol, Inceptisol, and Vertisol (Table 2.1). The microbial biomass is considered a significant reservoir of plant nutrients, specially N and P and also active fraction of organic matter. The more labile component of soil organic matter fractions are soluble phase of carbon and carbohydrates acts as source of plant nutrients better than most other fractions (passive pool of carbon). The most important biological properties of organic matter are (1) its role as a reservoir of metabolizable energy for soil microbial and faunal activities, (2) its effects in stabilizing enzyme activities, and (3) its values as a source of plant nutrition through mineralization. Thus, important approach to characterize soil biological health may be presented by inherent fluxes at which the soil microbial biomass would transmit the organic and inorganic growth stimulants, including the nutrients supply to the growing crops. Little attention has been paid towards labile pools of carbon as compared to total organic carbon in most agricultural soils. Typically, organic matter levels decline rapidly when soil under native vegetation is converted to arable

Table 2.1 Long-term effects of manure and fertilizer application on active fractions of soil organic carbon under inceptisol (rice-wheat-jute, R-W-J and 30 years), vertisol (sorghum-wheat, S-W, 15 years), alfisol (soybean-wheat, soy-W, 30 years), and vertisol (soybean-wheat, soy-W, 39 years) system at 0–15 cm soil depth

Locations (cropping system)	Treatments	SMBC (mg kg^{-1})	SMBN (mg kg^{-1})	AHC (mg kg^{-1})	SOC (g kg^{-1})	%POM in SOC
Inceptisol (R-W-J, 30 year)	Control	169	11.4	526	5.4	10.6
	N	162	10.7	580	5.7	16.5
	NP	209	11.0	609	6.3	22.4
	NPK	327	15.2	689	7.4	20.0
	NPK + FYM	486	20.2	845	7.9	27.0
Vertisol (S-W, 15 year)	Control	201	8.6	462	3.5	10.3
	N	220	10.2	590	3.4	23.3
	NP	244	12.3	620	3.9	26.7
	NPK	382	13.3	725	4.2	30.1
	NPK + FYM	465	16.4	840	4.5	39.7
Alfisol (soy-W, 30 year)	Control	154	7.8	328	3.5	10.0
	N	185	6.7	368	3.4	9.8
	NP	201	9.6	442	4.2	14.7
	NPK	210	12.2	466	4.5	26.7
	NPK + FYM	265	14.5	517	4.7	31.2
Vertisol (soy-W, 39 year)	Control	156	26.1	250	6.3	10.0
	N	218	32.2	370	6.4	10.4
	NP	382	41.6	415	7.0	9.8
	NPK	559	46.3	443	8.6	11.0
	NPK + FYM	598	49.8	448	12.4	13.3

Source: Manna et al. (2006, 2007, 2013a, b) control (without fertilizer, manure, and lime): N: 100% recommended rate of nitrogen; NP recommended rate of nitrogen and phosphorus; NPK: 100% recommended dose of nitrogen, phosphorus, and potassium; NPK + FYM: 100% recommended rate of NPK and 10 Mg ha^{-1} $year^{-1}$ FYM; *SMBC* soil microbial biomass carbon, *SMBN* soil microbial biomass nitrogen, *AHC* acid hydrolysable carbon, *SOC* soil organic carbon, and *POM* particulate organic matter

agriculture in the first 10–20 years and then stabilize at a new equilibrium level. Many factors contribute to loss of SOM levels such as lower allocation of carbon to the soil, removal or burning of crop residues, tillage induced aggregates disruption, more favorable condition for decomposition and greater losses of surface soil by water erosion. In agricultural soil, the light fraction typically contains 20–30% C and 5–20% N and 18–22% of total C and 1–16% of total N in the whole soil. Particulate organic matter (POM) contains 10–40% of total SOC and 13–40% of total N in the whole soil. The large POM maintains soil structure and macro-aggregation. The large amount of microbial community associated with the decomposing POM produces binding agent such as exo-cellular mucilaginous polysaccharides. It acts as a major food and energy for endogenic soil fauna. Thus, POM is associated with a multitude of soil process and functions and is therefore, a key attribute of soil quality. Acid hydrolysable carbohydrate (AHC) (32–37% of SOC) is a labile C fraction and has been found more rapidly in response to changes in management than SOC contents. The $KMnO_4$–oxidizable C fraction accounts for 5–30% of organic C. This oxidizable fraction usually is more sensitive to soil management than SOC. Long-term (39 years) application of balanced fertilizer either alone or in combination with manure has increased 3.2- to 3.6-fold of soil microbial biomass C, 1.8- to 2-fold of soil microbial biomass N, 1.8- to 2-fold of acid hydrolysable carbohydrates in Vertisol under soybean-wheat system as compared to fallow soil (Manna et al. 2013a, b). Over the years of cultivation of crops with application of balanced nutrients (NPK) maintained active fractions of C and N (Neogi 2014).

Thus, it is inferred from different long-term experiments that cultivation of double crops annually with imbalanced fertilization leads to greater nutrient loss that would have retain lesser amount of SOC and associate nutrients. Passive fraction of C and N pools are more resistant to decomposition and its mean residence time is about 500–1500 years. Long-term application of balanced fertilizer and manure significantly improved humic and fulvic acid fraction during 15–40 years in all the three soils (Inceptisol, Alfisol, and Vertisol) (Manna et al. 2007; Manna et al. 2013a, b; Joshi et al. 2017).

2.4 Slow Pool of Carbon

Both, in conventional tillage and zero tillage, fresh residue decompose and subsequently help developing different aggregate size classes (Fig. 2.2). However, in conventional tillage it decomposes much faster due to rapid oxidation in soil. In due course of time, the coarse fraction of interparticulate (iPOM) or heavy fraction of POM and fine iPOM or light fraction of POM are developed in the form of micro (53–253μm), followed by small-macro (250–2000 μm) and large macroaggregates (>2000 μm) aggregates. The time frame as mentioned in the figure indicated that the entire period for formation and disruption depends upon type and duration of tillage operation. In conventional tillage, the degradation of aggregates is more rapid than zero tillage operation. Thus, the practice of zero tillage may help to retain more POM in aggregates size classes than conventional tillage. Under intensive cultivation with multiple cropping systems, these carbon pools were significantly reduced due to reduction of large macroaggregates (>2 mm) and microaggregates (0.25 mm) that may reduce the heavy or light fraction of POM-C and POM-N, which resulted in low nutrient supplying capacity to soil (Manna et al. 2013a, b, Fig. 2.2). The application of recommended rate of NPK under soybean-wheat in Alfisol (30 years, Ranchi) and Vertisol (39 years, Jabalpur) and, rice-wheat in Vertisol (16 years, Raipur) improved the content of POMC and POMN by 5 to 38.6% and 5.2 to 28.5% compared to imbalanced N or NP treated soil (Manna et al. 2007; Joshi et al. 2017). The significant increase (48–72.4%) of mineral associated organic C and N (silt + clay

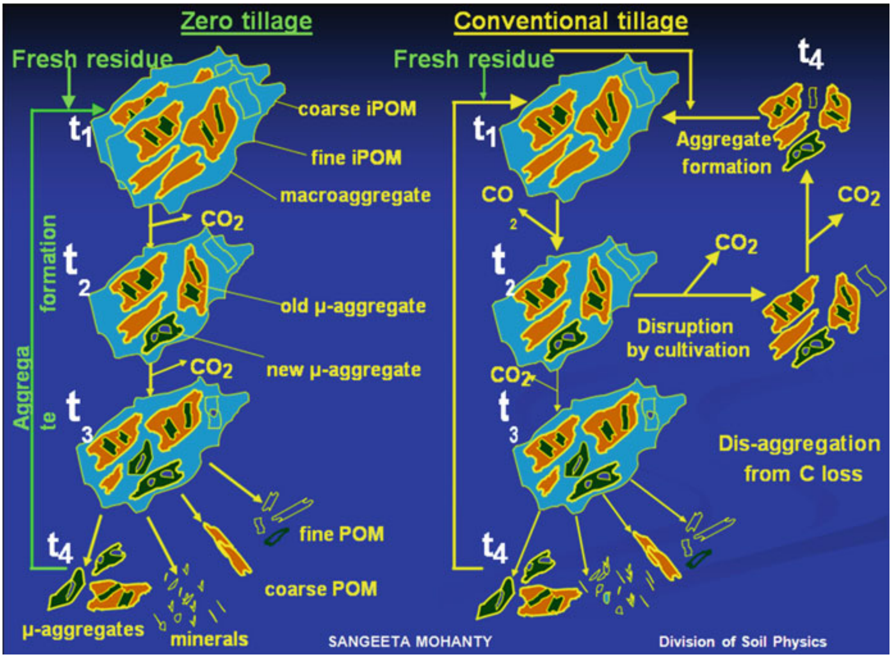

Fig. 2.2 Development and disintegration of soil aggregate's coarse and fine particulate organic matter in Zero–tillage and conventional tillage

Table 2.2 Long-term effect of manure and fertilizer application on C-mineralization rate (k) from aggregates of top soil layer (0–15 cm) in inceptisol

Treatment	0.25–2 mm k_c (mg kg^{-1} week^{-1})	0.053–0.25 mm k_c (mg kg^{-1} week^{-1})	<0.053 mm k_c (mg kg^{-1} week^{-1})
Control	0.022^{c}	0.040^{b}	0.030^{bc}
N	0.033^{c}	0.030^{b}	0.033^{bc}
NP	0.035^{c}	0.047^{b}	0.028^{bc}
NPK	0.051^{bc}	0.043^{b}	0.021^{c}
NPK + FYM	0.082^{a}	0.089^{a}	0.067^{a}

Computed through exponential model C_t = Co (1 − *e*-kt). Means with similar lower-case letters within a column are not significantly different at P < 0.05 according to LSD test

fraction) was found under long-term application of N, N-P application as compared to fallow. These studies clearly indicated the less retention of labile pools of nutrients due to rapid cultivation, resulted in deterioration of soil quality in a long run. The rate of C-mineralization from different aggregates was studied from long-term nutrient management system. It was found that C-mineralization was greater in macroaggregates size classes than microaggregates and least was observed in mineral associates (Table 2.2). Application of NPK with FYM significantly improved C-mineralization from all size classes.

2.5 Passive Pools of Carbon

A significant variation in the passive fraction of C by nutrient management is limited thereby indicate that more time frames are required to effect a change of passive pools, i.e. humic and fulvic acid (Manna et al. 2006; Joshi et al. 2017). However, the C stabilization is significant under different long-term land use and management practices and a greater extend the turnover time is estimated in the range of 10–100 years in the intermediate pools.

2.6 Steady State of C and Turnover Period

The basic information on carbon steady state and turnover period under different long-term nutrient management and cropping system may help to better understand of carbon equilibrium or quasi equilibrium under different soils. To study the steady-state C and turnover period, the model was used to describe the relationship between total SOC and cropping year. The value of K indicates how rapidly the SOC changes towards a new equilibrium level as computed the following equation.

$$\mathrm{SOC}_t = \mathrm{SOC}_e + (\mathrm{SOC}_0 - \mathrm{SOC}_e)\ \exp\ (-\mathrm{kt})$$

where SOC_t is the value of SOC (g kg^{-1}) at time t; SOC_e is the value of SOC at equilibrium; SOC_0 is the value of SOC at $t = 0$ (4.6 g kg^{-1} for Vertisol and 7.12 g kg^{-1} for inceptisol); k is the exponential rate of variation (1/year) and t is the cropping year. Continuous application of 100% recommended rates of NPK plus FYM established a new equilibrium of SOC much earlier ($t_{1/2}$, 2.4 years in vertisol, 7.7 years in inceptisol and 2.1 years in alfisol) than imbalanced use of either N or NP fertilizer ($t_{1/2}$, 8.1–25.7 years in vertisol, 14.9–50.3 years in inceptisol and 2.1–2.8 years in alfisol). Thus, this basic information generated can be very well used to sustain the yield, assessing the soil quality and restoring the degraded soil as a result of over exploitation of natural resources (Table 2.3).

2.7 Carbon Stabilization

Carbon storage and sequestration in agricultural soils is considered to be an important issue. In agro-ecosystem research, it is possible to differentiate three levels of crop production: Potential, Attainable, and Actual (Rabbinge and van Ittersum 1994; van Ittersum and Rabbinge 1997). Similarly, carbon sequestration in agricultural soils has also three situations, i.e. potential, attainable, and actual (Fig. 2.3). The amount of carbon present in the soil is the function of land use change, soil type, climate (rainfall and temperature), and management practices. This is due to:

$$\text{Clay content} - \text{physically protected} = \text{Potential C}$$

Table 2.3 Initial status of organic-C and equilibrium values for different treatments after 15 years and 30 years of cultivation of 0–15 cm depth at Akola and Barrackpore, India

Treatment	Initial SOC (g kg^{-1})	SOC_o mean (g kg^{-1})	Steady state (SOC) (g kg^{-1})	Loss rate (*k*, per year)	$t_{1/2}$ (year)	R^2
Akola (after 15 years of cultivation)						
N	4.6	4.6 ± 0.329	3.5 ± 1.798	−0.027	24.7	0.93*
NP	4.6	4.7 ± 0.067	4.4 ± 0.429	−0.086	8.1	0.86*
NPK	4.6	4.8 ± 0.093	4.6 ± 0.267	−0.138	5.02	0.84*
NPK+ FYM	4.6	5.4 ± 0.147	5.3 ± 0.374	−0.291	2.4	0.42
Barrackpore (after 30 years of cultivation)						
N	7.12	4.9 ± 0.025	4.8 ± 0.018	−0.020	50.3	0.10
NP	7.12	4.9 ± 0.065	5.0 ± 0.022	−0.067	14.9	0.22
NPK	7.12	5.0 ± 0.038	5.1 ± 0.04	−0.095	10.7	0.39
NPK + FYM	7.12	5.4 ± 0.022	5.6 ± 0.017	−0.129	7.7	0.62[a]

Source: Manna et al. (2013a, b)
*Value is significant at $P \leq 0.05$, ± standard error

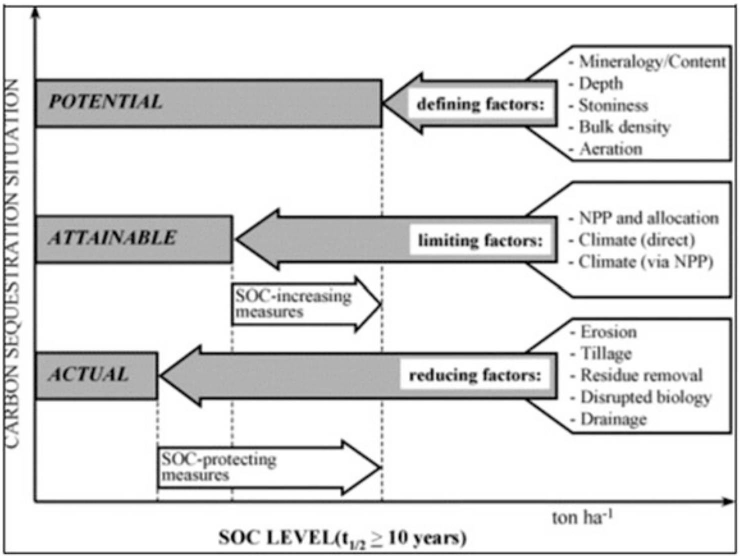

Fig. 2.3 Relationship between carbon sequestration situation and SOC level. Source: Adapted from Ingram and Fernandes (2001) and Manna et al. (2012)

$$\text{Climate} - \text{determines the net primary productivity} \\ = \text{Attainable C Management practices} = \text{Actual C}$$

Three terminologies are used in soil carbon sequestration study. They are $SOC_{potential}$, $SOC_{attainable,}$ and SOC_{actual}. The term "carbon sequestration potential," in particular, is used with different meanings; sometimes referring to what might be possible given a certain set of management conditions with little regard to soil factors which fundamentally determine carbon storage. Regardless of its potential, the amount of carbon a soil can actually hold is limited by factors such as rainfall, temperature, and sunlight and can be reduced further due to factors such as low nutrient availability, weed growth, and disease. The term "$Attainable_{max}$" is defined and is suggested as the preferred term for carbon sequestration in mineral soils, being more relevant to management than "potential" and thereby of greater practical value (Ingram and Fernandes 2001). The attainable soil C sink capacity is only 50–66% of the potential capacity (Lal 2004). $SOC_{potential}$ is the SOC level that could be achieved if there were no limitations on the system except soil type. Soil type has an influence because surfaces of clays and other minerals will influence how much organic C can be protected against decomposition. For a soil to actually attain $SOC_{potential}$, inputs of carbon from plant production must be sufficiently large to both fill the protective capacity of a soil and offset losses due to decomposition. Under dryland conditions (no irrigation) these factors will place a limit on the amount of residue that can be added to a soil such that attaining the $SOC_{potential}$ is not possible and a lower value defined as $SOC_{attainable}$ results. The value of $SOC_{attainable}$ is the realistically best case scenario for any production system. To achieve $SOC_{attainable}$, no constraints to productivity (e.g. low nutrient availability, weed growth, disease, subsoil constraints, etc.) must be present. Such situations virtually never exist and these constraints typically result in lower crop/pasture productivities than required to attain $SOC_{attainable}$. This second set of factors is referred to as reducing factors, which may well be under the control of farmers. Decreased productivity, induced by the reducing factors, leads to lower returns of organic carbon to soil and lower actual organic carbon contents (SOC_{actual}) (Baldock 2008).

It can be inferred that attainable level of organic carbon in Indian soils is generally limited by rainfall as we do not have much variation in mean annual temperature, although it may be limited in some areas and seasons. In this respect, use of simulation models like Roth-C and DSSAT-century could be the useful tool to determine the attainable level of soil organic carbon under different agro-ecological regions of the country. Using models to predict changes in organic soil carbon under different scenarios can provide an idea of the effects of different land uses and management practices, such as stubble burning, grazing pressure and fertiliser use. Models are able to estimate likely changes in organic soil carbon under a range of conditions, across a range of spatial scales and for much longer times than can be accommodated in experiments (Baldock 2008).

Regardless of potential, the amount of carbon a soil can actually hold is limited by factors such as climate, soil and can be reduced further due to factors such as nutrient availability, insect pest and disease incidence.

2.8 Impact of Organic Amendments Induced GHGs Emission and Management Practices for Mitigation

Global warming poses a major threat to the global environment and the major GHGs, the key contributor of global warming are originated from fossil fuel consumption (IPCC 2007; Pathak et al. 2009). Increased population and urbanization indicate rising shares of municipal solid waste (MSW), increase in food grain production generating plenty of crop residues, unscientific management of live stocks and poultry birds contributing considerable portion of CO_2, CH_4, and N_2O (Tables 2.4 and 2.5) in the atmosphere. The estimates of CO_2 emission from this untreated source may account for annual emission of approximately 5.2 and 155 Tg from MSW and animal waste and 198 Tg from crop residue manure (Table 2.4). MSW

Table 2.4 Potential of quantity of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission from municipal waste and animal waste

	Total population ($\times 10^3$)	Total quantity of biosolid produce ($\times 10^3$) (Mg/year)	CO_2-C (Gg/year)	CH_4-CO_2-C eq (Gg/year)	N_2O-CO_2-C eq (Gg/year)
	261,790	12,995	5198	612	442.7
	Total population ($\times 10^3$)	Total quantity of manure produce ($\times 10^3$) (Mg/year)	CO_2-C (Gg/year)	CH_4-CO_2-C eq (Gg/year)	N_2O-CO_2-C eq (Gg/year)
Cattle	299,606	355,483	142,193	34,452	9732
Sheep and Goat	200,242	30,010	12,004	4514	5934
Horse and Ponies	625	317	127	37	10
Pig	10,294	2574	1030	377	509
Poultry	729,209	1028	411	92	88
Total animal + poultry	1,239,976	389,411	155,765	39,472	16,272
	Cattle	Sheep and goat	Horse and ponnies	Pig	Poultry
Manure weight (kg/year)	1186.5	150	506.7	250.1	1.4
Total C (%)	34.7	53.85	41.4	52.4	32.2
Total N (%)	0.5	3.25	0.5	3.3	1.4

Sources: All emission factors are adopted from IPCC (1996) and Manna et al. (2018)

Table 2.5 Potential of quantity of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission from crop residue

Plant residue	Net area ($\times 10^3$) (ha/year)	Potential of residue ($\times 10^3$) (Mg/year)	TOC (%)	TN (%)	CO_2-C eq (Gg year)	CH_4-CO_2-C eq (Gg/year)	N_2O-CO_2-C eq (Gg/year)
Rice	42,750	210,480	45.3	0.61	841.9	26.631	7.81
Wheat	30,000	140,265	46.3	0.48	561.1	18.138	4.10
Sorghum	6210	15,840	44.8	0.52	63.4	1.982	0.50
Millet	7300	34,960	44.8	0.45	139.8	4.374	0.96
Maize	8670	100,170	52.5	0.52	400.7	14.688	3.17
Bengal gram	8520	11,479	47.8	0.8	45.9	1.533	0.56
Pigeon pea	3890	12,080	48.6	0.87	48.3	1.640	0.64
Lentil	1420	2260	45.9	1.21	9.0	0.290	0.17
Groundnut	4720	9400	41.9	1.6	37.6	1.100	0.91
Rapeseed	6290	16,060	45.9	0.67	64.2	2.059	0.65
Soybean	10,840	14,670	50	0.97	58.7	2.049	0.87
Sunflower	830	1620	39.7	0.53	6.5	0.180	0.05
Cotton	11,980	17,460	49.8	1	69.8	2.429	1.06
Sugarcane	5000	102,360	50.7	0.4	409.4	14.495	2.49
Potato	1990	34,912	45.8	0.52	139.6	4.466	1.10
				Total	2896.063	96.052	25.04

Sources: All emission factors are adopted from IPCC (1996), Manna et al. (2018)

generated in India is increasing at a rate of 1.33% annually (Shekdar 2009). It is estimated that overall N_2O losses from agriculture, animal, and municipal solid waste is about 45.73 Tg. The average per capita solid waste generation has been assessed to be 341 g of which 40% is biodegradable on dry weight basis and it shows that the estimates of GHG emissions from MSW was 5198 Gg CO_2, 612 Gg CH_4, and 442.7 Gg N_2O (Table 2.4) and GHG emissions from animal wastes in India was 155,765, 39,472, 16,272 Gg of CO_2, CH_4, and N_2O, respectively. During 2012, the contribution of crop residue towards GHG emission was 2,896,063 and 96,052 Gg of CO_2 and CH_4, respectively (Table 2.5).

Acceptability of mitigation options technologies need to be increased to reduce the net emissions of carbon dioxide, methane, and nitrous oxide. Nonetheless, the real challenge lies in the regional diversity of agricultural management practices which controls the rate of potential adoption of mitigation practices to accrue sustainable production and farmers benefit. Thus, the major challenge is how GHG emission can be reduced from agriculture, animal sector, and MSW management. Moreover, no quantitative information is still available on the total potential reduction in CO_2, CH_4, and N_2O emissions from existing croplands offsets by biofuel production. The emissions of CH_4 from composted farmyard manure and poultry manure-amended soils were very low. The practice of green manure application in rice field emitted lower CH_4 by methanogens than wheat straw as the easily biodegradable material content acted as with lower activation energy for microbes.

Application of surface mulching of straw during winter period reduced CH_4 emission compared to field incorporation. Composts consistently produced lower CH_4 emissions than fresh green manures or straws. Aerobic composting reduces readily decomposable carbon to CO_2 instead of CH_4. Low CH_4 production is highly influenced by inflow of oxygen and downward discharge of methanogenic substrate into the soil. In rice fields amended with biogas slurry emitted significantly less CH_4 than manure with wheat straw and in high-percolating site with rice field, CH_4 emission was extremely low. The main reason for low CH_4 emissions from rice fields in India is that the soils have very low organic C or receive very little organic amendments. Few measurements have been published for N_2O emissions from flooded rice soils amended with organic materials.

The existing information indicates that N_2O emissions from flooded soils with organic additions are similar to or less than the soils receiving chemical fertilizers, indicating that organic amendments do not appear to influence N_2O emissions very much. The dominant sources of N_2O in soils are biologically mediated reduction processes of nitrification and denitrification. In rice fields during periods of alternating wetting and drying N_2O occur as a result of nitrification–denitrification processes. Application of organic amendments like wheat straw, green manure coupled with nitrogenous fertilizer significantly reduced cumulative gaseous N losses.

High livestock density is always accompanied by production of a surplus of animal manure, representing a considerable pollution threat for the environment. Biogas is a smokeless fuel offering an excellent mitigation option for GHG emission from cattle dung cake, agricultural residues, and firewood, which are used as fuel in India.

2.9 Effect of Land Use and Management Practices on C-sequestration

Diversified cropping systems with better management substantially improved C-sequestration rate in semiarid-tropic soils of India (Manna et al. 2012). In vertisol, C-sequestration was maximum in castor + pigeon pea intercropping system (936 kg C ha^{-1} $year^{-1}$) followed by cotton/greengram + pigeon pea (885 kg C ha^{-1} $year^{-1}$), paddy-paddy system (861 kg ha^{-1} $year^{-1}$) then horticulture crop (citrus, 745 kg ha^{-1} $year^{-1}$) (Table 2.6).

The impact of long-term cultivation of crops in rotation and fertilizer and manure application on soil organic carbon stock, carbon sequestration rate, carbon sequestration efficiency have been computed in Inceptisol, Alfisol, and Vertisol (Manna et al. 2012). It was observed that the imbalanced fertilizer application (N and NP) was not encouraged for carbon sequestration rate and carbon sequestration efficiency in Inceptisol and Alfisol. However, treatment effect was prominently observed for

Table 2.6 Effect of different cropping system and management of C-sequestration rate in SAT benchmark soils of India

Location	Soil type	Cropping system	Study period	Sampling depth (cm)	Initial SOC $(\text{Mg ha})^{-1}$	Final SOC $(\text{Mg ha})^{-1}$	C-sequestrationrate $(\text{kg ha year})^{-1}$
Madhya Pradesh	Typic haplustert (Kheri)	Paddy–wheat	1982–2002	0–30	19.8	22.5	135
Maharashtra	Typic haplustert (Linga)	Citrus	1982–2002	0–30	22.0	36.9	745
Maharashtra	Typic haplustert (Asra)	Cotton/greengram + pigeon pea	1982–2002	0–30	17.3	35.0	885
Gujarat	Typic haplustert (Semla)	Groundnut–wheat	1978–2002	0–30	27.3	31.9	209
Karnataka	Typic haplustert (Teligi)	Paddy–paddy	1974–2002	0–30	18.61	43.6	861
Karnataka	Typic haplustalf (Vijayapura)	Finger millet	1982–2002	0–30	19.3	21.9	130
Andhra Pradesh	Typic halplustalf (Kaukuntla)	Castor + pigeon pea	1978-2002	0–30	14.5	35.1	936

Sources: Manna and Rao (2012)

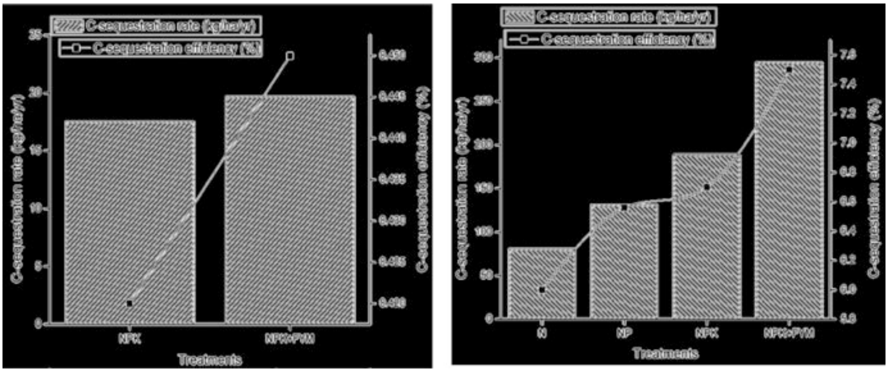

Fig. 2.4 Carbon sequestration rate and efficiency in (**a**) Inceptisol (**b**) Vertisol

C-sequestration efficiency and C-sequestration rate in Vertisol (Typic Haplustert) under sorghum-wheat system. Thus, SOC restoration process could be improved by a set of management practices in a long run. The results suggest that under high intensive cropping system recommended dose of inorganic NPK and NPK + FYM maintained soil quality parameters, which in turn supports better crop productivity and C-sequestration rate. In Inceptisol, the treatments with NPK and NPK + FYM showed lower carbon sequestration rate and it was varied from 17 to 22 kg/ha/year and C-sequestration efficiency was varied from 0.42 to 0.45% in these treatments (Fig. 2.4a). In Vertisol C-sequestration rate was varied from 75 to 300 kg/ha/year in N, NP, NPK, and NPK + FYM treatments (Fig. 2.4b) and C-sequestration efficiency varied from 5.8 to 7.5 % under sorghum-wheat system. The perusal of the graph signifies that carbon sequestration rate and efficiency depends on the type of soil and also cropping systems. It is clear that the C sequestration rate is higher in Vertisol than in Inceptisol. However, under high intensive cropping system recommended dose of inorganic NPK and NPK + FYM maintained soil quality parameters, which in turn supports better crop productivity and C-sequestration. The issue of climatic change and active and slow fractions of SOC and associate nutrients on productivity is needed more attention.

A significant build-up of SOC was found in 75% NPK+ FYM in soybean-wheat, sorghum-wheat, and soybean/sorghum-wheat system (Table 2.7). After 6 year of cultivation on an average SOC potential (CSP) was improved over initial SOC stocks from 2028 to 5292, 2028 to 4470, and 2343 to 5595 kg ha^{-1} at 0–30 cm in soybean-wheat, sorghum-wheat, and soybean + sorghum-wheat system, respectively. The SOC stocks in the plots of 0–15 cm depths in all these three systems were greater as compared to lower depth (15–30 cm). The C- sequestration rate (CSR) was greater in intercropping system followed by soybean-wheat system and sorghum-wheat system. Further it was observed that the C-sequestration potential was in the order: 75% NPK + FYM at 5 t ha^{-1} (F4) > 75% NPK + PC at 5 t ha^{-1} (F5) > 75% NPK + PM at 1.5 t ha^{-1} (F6) > 100% NPK (F3) > 75% NPK (F2) > control (F1).

Table 2.7 Effects of manures and fertilizer application on SOC stocks, C-sequestration potential (CSP) and C-sequestration rate (CSR) under different cropping systems

Treatments	SOC stock (kg ha^{-1}) after 6 year			CSP (kg ha^{-1})			CSR (kg ha^{-1} year^{-1})
	0–0.15 m	0.15–0.30 m	0–0.30 m	0–0.15 m	0.15–0.30 m	0–0.30 m	0–0.30 m
Soybean-wheat system							
F1	7776	6725	7250	−540	−205	−372	−62
F2	10,692	8610	9651	2376	1680	2028	338
F3	11,088	9240	10,164	2772	2310	2541	423
F4	13,860	11,970	12,915	5544	5040	5292	882
F5	13,662	11,550	12,606	5346	4620	4983	830
F6	11,880	11,130	11,505	3564	4200	3882	647
LSD ($P = 0.05$)	664.5	185.1	399.5				
Sorghum-wheat system							
F1	7736	6485	7110	−580	−445	−512	−85
F2	10,692	8610	9651	2376	1680	2028	338
F3	11,880	9030	10,455	3564	2100	2832	472
F4	13,266	10,920	12,093	4950	3990	4470	745
F5	12,078	9660	10,869	3762	2730	3246	541
F6	11,682	9660	10,671	3366	2730	3048	508
LSD ($P = 0.05$)	114.7	208.8	74.6				
Soybean + sorghum-wheat system							
F1	8526	7009	7767	210	79	144	24
F2	10,692	9240	9966	2376	2310	2343	390
F3	12,474	10,080	11,277	4158	3150	3654	609
F4	14,256	12,180	13,218	5940	5250	5595	932
F5	13,266	11,760	12,513	4950	4830	4890	815
F6	12,474	11,130	11,802	4158	4200	4179	696
LSD ($P = 0.05$)	168.5	237.8	138.6				

Control (F_1), 75% NPK (F_2), 100% NPK (F_2), 75% NPK + FYM at 5 t ha^{-1} (F_4), 75% NPK + PC at 5 t ha^{-1} (F_5), and 75% NPK + PM at 1.5 t ha^{-1} (F_6)

However, it was observed that the C-sequestration efficiency was greater in legume based cropping system and it was varied from 22.7 to 35.7% under soybean-wheat system followed by intercropping system (16.1–21.3%) and sorghum-wheat system (12.1–18.7%) (Fig. 2.5).

According to National Wasteland Development Board of India, the extent of degraded lands is around 158.06 million hectares (Table 2.8). It has been estimated that in India the forest cover has been depleted at the rate of 1.3 million ha^{-1} year^{-1} due to heavy pressures on forest lands for agricultural use and increased felling of trees to meet the requirements of the burgeoning human and animal population.

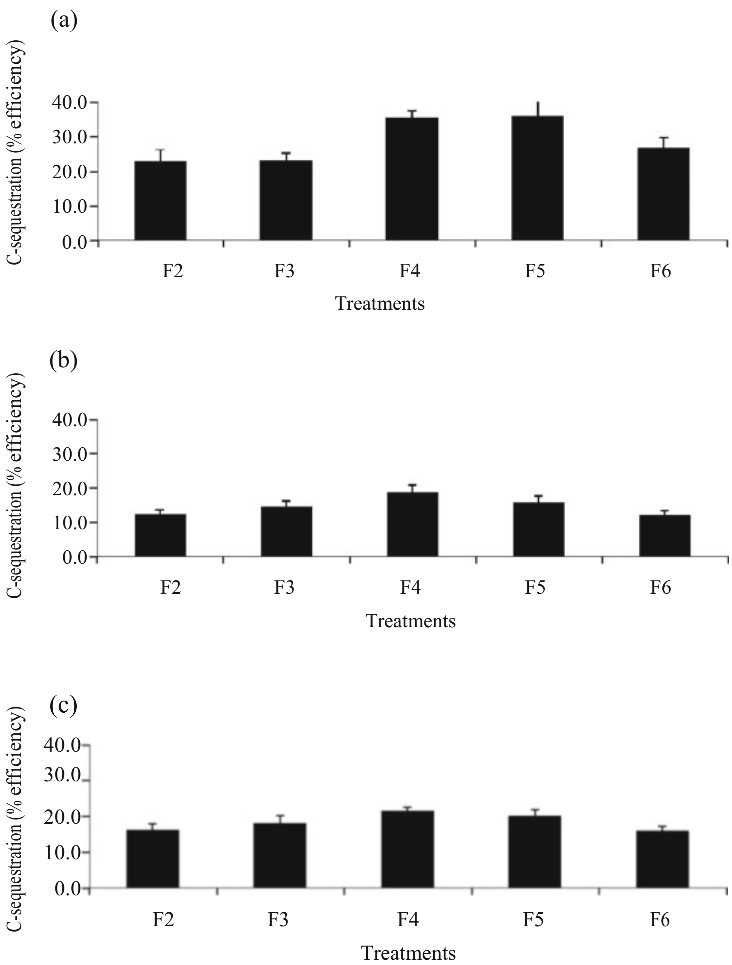

Fig. 2.5 Effects of fertilizer and manures on C-sequestration efficiency under three cropping systems (**a**) soybean-wheat, (**b**) sorghum-wheat, and (**c**) soybean + sorghum-wheat; error bars represents the standard error of mean; control (F_1), 75% NPK (F_2), 100% NPK (F_2), 75% NPK + FYM at 5 t ha^{-1} (F_4), 75% NPK + PC at 5 t ha^{-1} (F_5), and 75% NPK + PM at 1.5 t ha^{-1} (F_6)

Estimates of land areas affected by different soil degradation processes include 73.1 M ha by water erosion, 13 M ha by wind erosion, 3 M ha by fertility decline, 6 M ha by water logging, 7.5 M ha by salinization (Table 2.8). Such a deforestation trend in the world indicates that global climate will become warmer in the near future, due to increasing CO_2 concentration in the atmosphere. Many of these soils do not support any kind of vegetation except some perennial bushes and grass, which grow during the monsoon period. Wastelands, being extremely C depleted, have a relatively high potential for accumulating C in vegetation and soil if suitable trees and grass/crop species are grown, along with proper soil management practices.

Table 2.8 Categories of land under different types of wasteland in India

Number	Category	Ares (million hectares)
1	Water eroded	73.60
2	Degraded forest	40.00
3	Riverine	2.73
4	Ravines and gullies	3.97
5	Shifting cultivation	4.36
6	Sand dunes	7.00
7	Water logged	6.00
8	Saline/alkaline wasteland	7.50
9	Wind eroded	12.90
	Total	158.06

Source: Jha (1995)

Establishing permanent vegetative cover of trees and herbaceous plants on waste land will add to the SOC levels in the soil and reduce C loss through decomposition by moderating the temperature.

For example, one hectare of new forest will sequester about 6.2 tons of C annually, whereas 118 million ha wastelands as reported by Sehgal and Abrol (1994) have the potential to sequester nearly 1165 million tons of C annually. Lal (2004) computed carbon sequestration potential of Indian soils by assuming converting degraded soils to restorative land use and estimated total potential of 39 to 49 (44 ± 5) Tg C year^{-1}. According to him, Indian soils have considerable potential of terrestrial/soil carbon sequestration. They estimated the soil organic carbon (SOC) pool of 21 Pg to 30-cm depth and 63 Pg to 150-cm depth. The soil inorganic carbon (SIC) pool was estimated at 196 Pg to 1-m depth. The SOC concentration in most cultivated soils is less than 5 g/kg compared with 15–20 g kg^{-1} in uncultivated soils. Low SOC concentration in soil is attributed to plowing, removal of crop residues and other bio-solids and mining of soil fertility. Accelerated soil erosion by water leads to emission of 6 Tg C year^{-1}. Important strategies of soil C sequestration include restoration of degraded soils and adoption of recommended management practices (RMPs) of agricultural and forestry soils. Potential of soil C sequestration in India is estimated at 7–10 Tg C year^{-1} for restoration of degraded soils and ecosystems, 5–7 Tg C year^{-1} for erosion control, 6–7 Tg C year^{-1} for adoption of RMPs on agricultural soils, and 22–26 Tg C year^{-1} for secondary carbonates.

2.10 Strategies to Enhance SOC

Strategies for enhancing the productivity of rainfed crops and cropping systems and storage of SOC on sustainable basis are as follows:

1. Correction of limiting nutrient(s) including micronutrients and site-specific nutrient management approach in rainfed areas can help in augmenting the productivity.
2. Inclusion of short duration legumes in cropping systems.
3. Green leaf manuring with the help of nitrogen fixing trees like Gliricidia and leucaena and off-season biomass generation and its incorporation.
4. Recycling and enhancing the quality of organic residues using effective composting methods.
5. Capitalization of the potential of microbes/bio-fertilizers.
6. Linking agricultural practices with short and long-term climatic forecast.
7. Adoption of site-specific soil and water conservation measures.
8. Appropriate crops and cropping systems for wider climatic and edaphic variability.
9. Enhancing the input use efficiency using the principle of precision agriculture.
10. Diversified farming systems for enhanced income and risk mitigation.
11. Ensuring credit, market access and crop insurance.
12. Controlling top soil erosion.
13. Conservation tillage (specially reduced and zero tillage) and surface residue management, mulching, etc.
14. Balanced and adequate fertilization and integrated nutrient use.
15. Carbon sequestration through agro-forestry tree species and its recycling by leaf litter fall.
16. Use of soil amendments.
17. Regular use of manures.

2.11 Future Research

Central questions that need to be addressed in the era of global warming revolves around (1) the temperature sensitivity of soil OM, especially the more recalcitrant pools; (2) the balance between increased carbon inputs to the soil from increased production and increased losses due to increased rates of decomposition; and (3) interactions between global warming and other aspects of global change including other climatic effects (e.g., changes in water balance), changes in atmospheric composition (e.g., increasing atmospheric CO_2 concentration) and land use change. A number of possible technologies to mitigate the worst impacts of climate change are available, mainly in managed systems. These technologies, which promote soil carbon stabilization and sequestration, will also help mitigate climate change itself (by reducing atmospheric CO_2 concentrations) and are cost competitive with mitigation options available in other sectors. Some warming will occur and it is important that humans adapt management practices to cope with this change, but soils also provide a great opportunity, along with a raft of other measures, to slow that rate of warming. Identifying the "win–win" options that deliver both adaptation and mitigation and finding ways to implement these measures, remains one of our greatest challenges for this century.

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3 Soil Organic Carbon: Past, Present, and Future Research

Emma Chappell, Tahmid Huq Easher, Daniel Saurette, and Asim Biswas

Abstract

Maintaining soil health is critical to meet agricultural production demands. Soil health is the capability of soil to function as a living system within an ecosystem, to support production, to maintain or enhance water and air quality, and to promote plant/animal health. Soil organic carbon (SOC) is the backbone of soil health. Intensive agricultural management has led to a reduction of SOC globally. Scientific communities, along with the policy makers and different stakeholders, have been putting enormous efforts in improving and maintaining SOC stocks in the quest of achieving agricultural sustainability to meet the demand of ever-increasing population. Also, the potential of soil to sequester carbon as a climate change mitigation strategy, has led climate and soil scientists in performing ground-breaking research focusing on SOC. Thus, this book chapter focuses on the importance of SOC on soil health, strategies to improve it, the past and ongoing research on SOC, and the future direction of estimating SOC.

Keywords

Soil health · Soil carbon stocks · Carbon research · Machine learning algorithms · Monitoring soil carbon · Soil carbon across time

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3.1 Introduction

As the world's population continues to grow, there is concern that the world's soil and its health will be degraded to meet agricultural production demands (Lucas et al. 2014). Soil health is the capability of soil to function as a living system within an ecosystem, to support plant and animal production, maintain or enhance water and air quality, and to promote plant and animal health (Doran and Zeiss 2000). Changing climate, economy, and agricultural management are contributing to the degradation of soil health (Kerr 2018), which threatens our ability to meet the increased food, feed, fuel, and fiber demand (Lucas et al. 2014). Soil organic matter (SOM) is a main indicator of soil health due to its important role in plant growth, soil structure development, and maintenance of soil pH (Stockmann et al. 2013). Soil organic matter is comprised of carbon (C), oxygen, hydrogen, nitrogen, phosphorus, and sulfur from plant litter and animal material/waste, with C being present in the largest quantities (~58% C in SOM). This makes SOM the largest terrestrial pool of C (Yadav and Malanson 2007). Unfortunately, intensive agricultural management and production has led to a reduction of SOM overtime at a global scale (Liu et al. 2006). Reduced SOM levels have resulted in increased greenhouse gas emissions (GHGs) and erosion potential, as well as reduced water infiltration and water quality (Banwart et al. 2015). As climate is changing, there is a rising interest in the understanding of soil organic carbon (SOC) since it has the potential to mitigate climate change through C sequestration and C cycling (Yadav and Malanson 2007). If C cycling in soils is poorly understood, then there will be misguided efforts to mitigate climate change. Understanding cycles, decomposition rates and how changes in different substrates, temperature and temporal scales are imperative to gaining insights on SOM and SOC cycling within soils (Alvarez et al. 2018; Kleber 2010). Having a complete knowledge of SOM and SOC cycling is critical so that measures can be taken to restore soil health while maintain necessary production levels and to potentially mitigate changes in climate.

Farmers have known for millennia that their crop and soil management activities influence the health and fertility of soils, including the SOM content (Fig. 3.1). Being able to quantify SOC stocks is a critical step in the restoration of soil health as it allows producers to make more informed agricultural management decisions and is important for developing accurate climate change mitigation projections. Intensive management of agricultural soils all over the world has resulted in significant SOC stock declines. Carbon stock declines have inspired researchers to measure SOC in agricultural fields so that ways to increase soil C stocks can be found. There is often an agricultural focus in SOC research as past agricultural management has resulted in significant losses. This focus indicates that SOC stocks are highly responsive to land use and management practices in agricultural settings (Vitharana et al. 2019; Gnanavelrajah et al. 2008). Providing accurate estimates of SOC stocks will help producers to assess the fertility of their soil, thus helping them to decide the soil preparation and management practices used to achieve agricultural resilience (Paustian et al. 2017). Figure 3.2 shows some techniques that productions could use to increase SOC in agricultural areas.

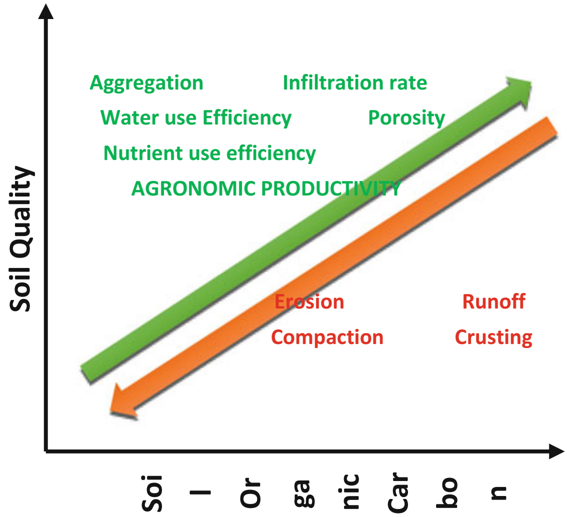

Fig. 3.1 The Importance of Increasing Soil Quality by Increasing Soil Organic Carbon. (Adopted from Lal 2007)

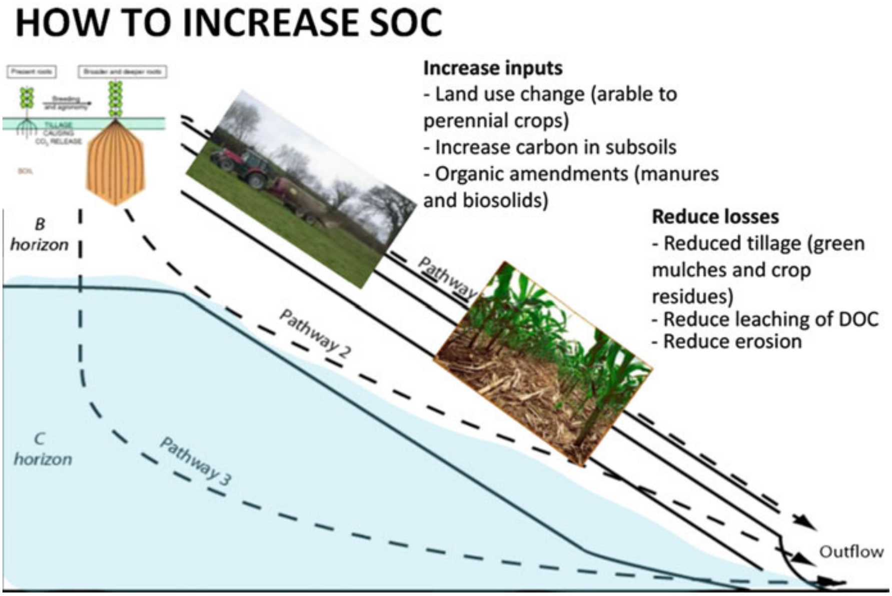

Fig. 3.2 Techniques to Increase SOC in Agricultural Field (Adopted from Kell 2011)

3.2 Soil Organic Carbon Research

3.2.1 Estimating Soil Organic Carbon Stocks

Scientific studies have been carried out for nearly two centuries (Russell 1953) to determine the impact of various crop and soil management practices on SOM and resultant crop responses. Prior to the late 1980s, studies of SOM dynamics were almost exclusively done in the context of how changes in SOM influence soil physical properties (e.g. infiltration, porosity) and nutrient availability, both of which affect crop growth. These early field studies and models remain relevant to the core knowledge of SOC dynamics. As these early studies relied heavily on field experiments, they tended to be very time-demanding, laborious, and expensive. The purpose of these studies was to estimate SOC stocks to improve base knowledge so that the effects of future land use and climate changes could be better understood (Hontoria et al. 1999). There was an effort to understand the relationship between SOC and environmental factors, i.e., precipitation, temperature, elevation, slope gradient, and land use, so that the magnitude and consistency of changes in SOC stocks could be understood (Liu et al. 2011; Zinn et al. 2005). The focus was not only agricultural, but environmental, as researchers were concerned with the effect changing SOC stocks would have on the atmospheric carbon dioxide (CO_2) reservoir (Hontoria et al. 1999). Many studies found that land use change from forest to cropland resulted in significant losses of SOC (Zinn et al. 2005).

3.2.2 Improving Soil Organic Carbon Stocks

As scientists realized that global SOC stocks were declining, research focus shifted from estimating stocks to improving stocks. There was concern that lowering SOC stock would result in environmental degradation and food shortages worldwide. The conversion of natural ecosystems to agriculture affects the rate of additions and loses of SOM, as agricultural land was expanded to meet the food demands of the growing population, global SOC stocks decreased (Zinn et al. 2005). In efforts to remedy this, strategies were developed to improve SOC stocks worldwide. Two strategies that were intensively researched were best management practice (BMP) implementation in agriculture and afforestation to establish more forests. Early studies on how management could be used to increase SOM through removing more CO_2 from the atmosphere, i.e., climate change mitigation through C sequestration, (Barnwell et al. 1992) relied on field experiments (Paul et al. 1997) and models (Powlson 1996; Paustian 1994) that were originally designed to study SOM as a soil fertility factor. Don et al. (2011) found that the conversion of forest into agricultural land for agricultural expansion always led to SOC loses but these loses are reversible to a high degree if the land is afforested or properly managed.

Best management practices could help to increase SOC stocks globally by slowing down the rate of decomposition and increasing the additions to the system. For this to increase the global stocks, it would need to be adopted on a wide scale, which may not be feasible. The goal of using BMPs is to maintain production while minimizing the negative effect of agricultural production on the surrounding environment. Some examples of BMPs are adopting less intensive tillage practices, reducing reliance on pesticides, and other inputs, using cover crops to keep the soil covered year-round, managing manure, and working crop residues back into the system (Smith et al. 2008). The physical disturbance of tillage is especially impactful when it comes to speeding up the rate of decomposition making tillage reduction very impactful regarding increasing SOC (Zinn et al. 2005; Govaerts et al. 2009). Unfortunately, the level of adoption of BMPs by producers varies from region to region.

Conservation agriculture (CA) is another SOC focused management strategy but is more feasible than BMPs. Conservation agriculture works to increase SOC stocks by minimizing soil disturbance, diversifying crops rotations, and residues while increasing crop yields, reducing soil degradation, and developing more weather resilient systems (Powlson et al. 2016). Conservation agriculture is made up of three principles: low-zero tillage, more than 30% soil cover, and increased crop rotations (Powlson et al. 2016; Jat et al. 2012). There is some concern regarding the feasibility of CA in tropical areas where there is competition for crop residues between animal feed and soil retention (Powlson et al. 2016). Conservation agriculture is believed to be a more favorable than BMPs because it is less extreme and can be adopted on a larger scale, but there are concerns regarding large SOC estimation errors making it not as effective for raising SOC stocks as it was originally believed to be (Powlson et al. 2016; Jat et al. 2012).

The studies that focused on afforestation, the practice of planting trees on land that was once used for agricultural purposes (Paul et al. 2001), concluded that afforestation could increase SOC stocks (Don et al. 2011). Laganiere et al. (2010) found that the positive effect of afforestation on SOC stock was greater in areas that were previously cropland as opposed to pasture or natural grasslands. This is due to the greater level of disturbance in croplands. Generally, there is an initial decrease in SOC after afforestation but as the trees establish themselves and produce more biomass, there is a gradual increase in SOC (Paul et al. 2001). Broadleaf tree species have a greater capacity than coniferous species to accumulate SOC (Laganiere et al. 2010). After about 30 years of establishment, the C content of the top 30 cm of soil is greater than the C content of the previous agricultural soil (Paul et al. 2001). While this method is effective for raising SOC stocks, afforestation does not make sense on a large scale as agricultural land is needed to meet the rising food production demands.

3.2.3 Monitoring Soil Organic Carbon Over Time

Moving forward, to have a good understand of SOC stocks, soil monitoring of SOC across time and landscapes must be completed so that SOC pools and changes can be assessed (Hartemink et al. 2014). Since many soil properties and functions change slowly over a long-term, it is important to carry out research that looks at SOC over a period, instead of a point in time (Stockmann et al. 2015). Research that investigates SOC over time should be done for more than 5 years to account for long-term changes to the soil (Hartemink et al. 2014; Dean et al. 2012). While previously collected SOC data can be used in these studies, there is the challenge of a lack of uniformity across SOC studies when it comes to methods, units of measurements, and presentation of results, concentrations vs mass per volume (Hartemink et al. 2014). For this reason, only certain studies completed in the past could be used for time-based measurements, and that a uniform sampling methodology needs to be developed. In the past it would have been difficult to carry out a long-term study of SOC due to sampling related time constraints and costs, but due to advances in proximal soil sensing technologies which can greatly reduce to cost of sampling (McBratney et al. 2003) large amounts of data can be collected efficiently. Stockmann et al. (2015) carried out a global assessment of SOC concentrations spatially and temporally finding that land cover change is the primary factor that influences SOC change over time, followed by temperature and precipitation. The researchers are hopeful that the completion of SOC stock change maps that incorporate both landscape and time will allow us to be able to assess soil health and determine when we are close to reaching critical thresholds of sustainability (Stockmann et al. 2015). The completion of this research on a large scale would also help to validate the potential of C sequestration as a climate change mitigation strategy (Smith et al. 2020).

3.3 The Future of Quantifying Soil Organic Carbon Stocks

As technology advances, opportunities arise to use digital soil mapping (DSM) based machine learning (ML) to estimate SOC stocks. Advancement and development in these areas have made it possible to estimate SOC stocks efficiently by reducing the time, labor, and cost requirements associated with determining SOC across an area. Many machine learning algorithms can be used in DSM to combine data and compute maps. Geographic information systems (GIS), by itself, are not able to map soils without an intellectual framework to go off and this is where ML algorithms become necessary for mapping (McBratney et al. 2003). DSM has allowed SOC maps to be shared across large areas, increasing the accessibility of producers to important management altering information. Still, it is in the testing phase to determine the best ML practice to use to estimate soil properties as there are questions regarding the accuracy of the output maps. As time goes on it is believed that ML techniques will become more reliable and accurate as the best aspects from previous methods will be kept and the worst aspects disregarded (Malone et al. 2013).

Conventional polygon-based soil C maps, which limits resolution and do not adequately express the complexity of soils across a landscape in an easily understandable way, are being replaced by digital maps of soil C stock. DSM techniques not only can estimate SOC stock but also quantify associated uncertainties (Lamichhane et al. 2019). These techniques are been used in both creating new map areas and updating the previous maps. They have the advantage of handling, analyzing, and interpreting large volumes of geospatial data as they are stored in digital spatial formats (Grunwald 2009; Meersmans et al. 2009; Triantaflis et al. 2009).

The foundation of digital soil C mapping was based on the SCORPAN factor (Jenny 1941) and formulated by Minasny et al. (2013) as $C_x = f(s, c, o, r, p, a, n) + e$, where soil C at "x" spatial location is a function of soil properties', climate "c," organisms "o"(vegetation, fauna, anthropogenic land use, and management practices), relief "r" (terrain features and parent materials), age of soil "a," spatial position "n," and the error "e" (the spatial trends which were not accounted by the predictive factors). These soil-forming factors have been used as environmental covariates in DSM techniques to estimate SOC stock (Zhang et al. 2017). Also, various data mining and predictive algorithms are being tested for their suitability in optimizing the prediction of SOC, using DSM methodologies (Lamichhane et al. 2019).

Existing soil information or legacy soil maps are being used as a covariate (McBratney et al. 2003; Wiesmeier et al. 2011) to predict SOC stock, the prediction model of Adhikari et al. (2014) using legacy soil maps as covariates was reported to have an accuracy of 60% for predicting SOC. Soil classes and properties such as texture, bulk density, and clay mineralogy as covariates were reported to have a strong correlation with SOC and can explain its variability (Jobbágy and Jackson 2000; Badgery et al. 2013). Parent material information such as bedrock geology can be influential in mapping SOC for a wider landscape and subsurface soils as covariates, as it influences SOC level with increasing depth in the soil profile (Wiesmeier et al. 2011; Adhikari et al. 2014; Gray et al. 2015). Various climatic parameters like precipitation and soil moisture (Adhikari et al. 2014; Hobley et al. 2015; Wang et al. 2018a), surface temperature (Hobley et al. 2015; Rial et al. 2017a; Sayão and Demattê 2018), solar radiation (Kumar et al. 1997; Adhikari et al. 2014), etc. play influential role in estimating SOC content using DSM techniques, especially in the topsoils. In digital soil C mapping, present and past datasets from legacy field surveys and existing remote sensing-based sources have been used as covariates for representing organism factors like land use and cover (Wiesmeier et al. 2011; Minasny et al. 2013; Rial et al. 2017a; Hinge et al. 2018), vegetation conditions (Yang et al. 2007; Bui et al. 2009; Wang et al. 2018a), and influence of prevalent biota (Paul 2016; Weil and Brady 2016), which are highly correlated with SOC at topsoil at different scales and geographic extents. Especially the time-series images of vegetation cover from big cloud-based databases and platforms like Google Earth Engine (Kumar and Mutanga 2018) can improve the prediction of SOC significantly (Wilson and Lonergan 2013; Padarian et al. 2017; Rudiyanto et al. 2018). To predict SOC using DSM, relief factors like Digital Elevation Model (Ma et al. 2017), terrain attributes (Mahmoudabadi et al. 2017), topography (Wang et al. 2018b), elevation (Hinge et al. 2018), slope (Qin et al. 2012), etc. are highly recommended to use as covariates due to their influence on soil organic level.

Using ML and DSM to accurately estimate SOC stocks will be beneficial as this information can be used to develop climate change mitigation strategies. In 2010, for the first time, a set of specifications of soil properties (including soil C) for digital soil mapping were provided by the GlobalSoilMap project at 100 m spatial resolution across the world (Arrouays et al. 2014; Hempel et al. 2014). In 2017, the Global SOC map (GSOCmap) of the topsoil (0–30 cm) at one-kilometer resolution was initiated to be developed with the partnership of the Global Soil Partnership (GSP 2017) and the Intergovernmental Technical Panel on Soils (ITPS). This was a country-driven approach for which GSP provided technical assistance, training, and standardized specifications to generate national SOC maps (GSP 2017). The first version of the global soil C map, launched on World Soil Day on 5 December 2017, is available online (GSOC Map 2017). Also, Hengl et al. (2015) developed an improved version of Soil Grids at 250 m resolution, which performed the global predictions for different soil properties (organic C, bulk density, cation exchange capacity, pH, soil texture fractions, and coarse fragments) at seven standard depths (0, 5, 15, 30, 60, 100, and 200 cm). This approach used machine learning instead of linear regression, prepared covariate layers in finer resolution, and inserted additional soil profiles to estimate SOC and other soil properties.

Different simple linear statistical models (Moore et al. 1993), geo-statistical and hybrid approaches (Minasny et al. 2013), and various machine learning (ML) techniques (Zhang et al. 2017) have been used to predict SOC stock and distribution, using DSM techniques. Among all the available techniques, Regression Kriging (Keskin and Grunwald 2018), Random Forest (Yang et al. 2016; Siewert 2018), Boosted Regression Tree (Ottoy et al. 2017), Cubist (Kuhn et al. 2018), Geographically Weighted Regression (Tan et al. 2017), Support Vector Machine (Were et al. 2015), Artificial Neural Network (Zhao et al. 2010) comparatively performed better in predicting SOC. Although the performances of these models are inconsistent, thus they need to be calibrated with specific datasets with suitable algorithms and validated with external datasets to ensure better performances from the models (Brus et al. 2011).

In addition to the mapping of SOC concentration and stocks, there have been some trends in mapping SOC in other dimensions using DSM approach. Chen et al. (2018) mapped C sequestration potential in France and stated that subsoils have a higher potential of C sequestration than topsoils. Several recent DSM studies have mapped the changes in the SOC concentration levels and stocks with current and projected land use/land cover and different climate change scenarios (Gray and Bishop 2016; Rial et al. 2017b; Rojas et al. 2018; Yigini and Panagos 2016; Zhou et al. 2019). These maps will help in visualizing different probable scenarios and proactive planning in climate change mitigation and C sequestration projects.

3.4 Conclusion

Accurate information on SOC estimation is crucial to the development of a new soil information service, the need for which is building. There has been substantial progress toward recognizing the key role of SOC in relation to many core ecosystems services, as well as in measuring and modeling changes in SOC pools in response to both environmental and agricultural management factors. As a result of this progress, entrepreneurial programs and methods are being developed that can help lead the way toward a more comprehensive inclusion of SOC in farmers' decision-making going forward. While many issues still require significant research and attention like questions regarding co-benefits and trade-offs of practices that maximize SOC, the need to ensure food security and equitable outcomes, open data and privacy issues, etc.; a critical mass of information is now available and serves as a foundation for forwarding movement. Also the lack of information on soil C stock means that variation in overall C stocks in soil with environmental or regional geomorphic characteristics such as climate, glacial history, marsh type, tidal amplitude, and soil depth are effectively unknown. This illustrates the great need for more research into the main variables affecting SOC stock going forward towards a sustainable soil management and climate change mitigation.

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Belowground Carbon Storage and Dynamics

4

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Abstract

This chapter explores the importance and prospects of soil organic carbon (SOC) sequestration for addressing the present day challenge of food and nutritional security and mitigation as well as adaptation to global climate change scenario. Soil organic matter (SOM) is dynamic and vital to soil fertility. Long-term storage of SOC through sequestration in soil has strategic importance in mitigating climate change and improving soil quality. Therefore, an accurate estimation of SOC stocks is necessary which strongly depends on baseline SOC values and involves the quantification of (a) organic carbon concentration of the given soil depth and (b) soil bulk density. Such measurement should be done on equivalent mass basis to avoid imprecision due to presence of residues or changes in bulk density by tillage. The main mechanisms behind SOM stabilization are chemical stabilization, physical protection, and biochemical stabilization. All these processes function by protecting the SOM from microbial decomposition and eventually reducing its decomposition rate in soils. Soil organic carbon sequestration depends on adoption of management practices that increase the amount of carbon stored in soil. The strategies suggested here for SOC sequestration especially in Indian context are integrated nutrient management, conservation agriculture, agroforestry, crop diversification, prevention of soil erosion, and restoration of degraded lands. These C sequestering practices act by increasing the rate of input of organic matter to soils and/or by reducing the turnover rates of SOC stocks already present in the soil. The benefits of SOC sequestration are immense; however, challenges are being encountered which needs to be taken care of.

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4.1 Introduction

Soil organic carbon (SOC) is dynamic, and anthropogenic impacts on soil can turn it into either a net sink or a net source of greenhouse gases (GHGs). The green revolution steered intensive cultivation, which concentrated on sole mineral fertilizer, barring the organics, resulted in decreased SOC. The term "soil C sequestration" implies removal of atmospheric CO_2 by plants and long-term storage of carbon in oceans, soils, vegetation (especially forests), and geologic formations, which cannot be easily reemitted back to the atmosphere. Soil C sequestration plays critical role in balancing environmental C cycle. Based on the multi-dimensional roles of SOC, a popular approach called "4 per 1000 Initiative: Soils for Food Security and Climate" was launched by France during the COP21 which sets a target of 4 per 1000 (i.e., 0.4%) rate of annual increase in global soil organic carbon (SOC) stocks for addressing the three-fold challenge of food security, adaptation to climate change, and mitigation of anthropogenic GHG emissions (Soussana et al. 2019).

In this context, understanding the content and dynamics of belowground stored or sequestered C is of utmost importance. The primary way of C sequestration is through encapsulation or storing inside soil organic matter (SOM). The SOM is a complex mixture of carbon compounds, consisting of decomposing plant and animal tissues, microbes (protozoa, nematodes, fungi, and bacteria), and carbon associated with soil minerals. Carbon may remain stored in soils for millennia, or be quickly released back into the atmosphere. Therefore, our strategy should be to increase SOC density, improve depth distribution of SOC, and stabilize SOC by encapsulating it within stable aggregates. In this chapter, we will discuss different mechanisms responsible for improving belowground C storage, means of measuring SOC sequestration and the agricultural management strategies that could enhance the above-mentioned process.

4.2 Importance of Soil Organic Carbon Sequestration

Anthropogenic activities, like burning of fuels, deforestation, increased tillage of agricultural fields, indiscriminate uses of mineral fertilizers, have led to an increased level of atmospheric CO_2 from 280 ppm in the pre-industrial era to current level of ~400 ppm (WMO 2015). Climate change poses a major threat to food security through it's strong impact on agriculture, due to their inter-dependence on each other. This emphasizes the role of SOC sequestration and its strategic importance in mitigating climate change and improving soil quality. The SOC acts as an indicator of soil quality, as it governs most of soil physical, chemical, and biological properties (Fig. 4.1). Soil organic matter is vital for soil structural stability, by virtue of promoting soil aggregate formation. This improves soil porosity, ensures sufficient aeration and water infiltration to support plant growth. High SOC improves bio- availability of plant nutrients, enhances soil moisture dynamics. Through SOC sequestration, a part of the photosynthesized biomass is converted into stable humus (with a long mean residence time), which can reduce atmospheric GHGs and

Fig. 4.1 Relation of soil organic carbon to soil quality (Source: Lal 2013)

subsequently offset climate change and global warming, in the long run. On the other hand, through accelerated SOC mineralization, soils can be a substantial source of GHG emissions into the atmosphere. Soils depleted of SOC not only yield less, but also have low use efficiency of added inputs. This may decrease the soil structural stability, increase soil's susceptibility to water runoff and erosion, disrupt cycles of water, carbon (C), nitrogen (N), phosphorus (P), sulfur (S), and other elements, and cause adverse impacts on biomass productivity, biodiversity, and the environment.

The global C sequestration potential of arable soils is estimated ~2.1 billion tons C per year (Lal 2010). If the SOC pool in world soils can be increased by ~10% (+250 billion tons) over the twenty-first century, it implies a depletion of ~110 ppm of atmospheric CO_2 (1 billion tons of soil C = 0.47 ppm of atmospheric CO_2). The beneficial impact of increasing the SOC pool on soil quality and agronomic production is often more on degraded soils with severely depleted SOC pool. In India, about 120.7 Mha is under degraded lands (Bhattacharyya et al. 2015) suggesting a better scope for sequestration and restoration of SOC in these soils.

4.3 Surface Carbon Vs Deep Soil Carbon Sequestration

Soil contains ~1550 Gt of organic carbon globally in 1 m depth. The soil C pool (SOC along with soil inorganic carbon) is 3.3 times the size of the atmospheric pool (760 Gt) and 4.5 times the size of the biotic pool (560 Gt) (Lal 2013). The SOC pool of 1-m depth ranges from 30 t/ha in arid climates to 800 t/ha in organic soils of cold regions, predominately in between 50 and 150 t/ha. Major importance is given to surface or root zone SOC, i.e., within 30 cm soil layer, which is having a direct bearing on crop growth. However, often-shallow soil sampling to 30 cm underestimates SOC sequestration. Shallow soil sampling is often justified by assuming that deeper soil horizons are stable and will not change over time and SOC concentration per se is less in lower depths. Despite their low C contents, most subsoil horizons contribute to more than half of the total soil C stocks (Rumple and Kögel-Knabner 2011). Therefore, it is plausible to consider deep SOC sequestration in the global C cycle. The global SOC pools of 2 and 3 m- depth soils are ~2344 (Jobbagy and Jackson 2000) and ~2400 Pg (Batjes 1996), respectively. Measurement of surface SOC sequestration is critical when some short-term benefits are considered, including changes in tillage, fertilization, and residue management. However, deep SOC sequestration should be measured when the whole eco-system is considered over a larger period. Hobley et al. (2016) reported that depth was the key determinant of the allocation of SOC to its component fractions, with enhanced proportions of humus found in increasingly deep soils, concurrent with a depletion of particulate organic C. Deep SOC registered very high mean residence time, often up to several thousand years (Gaudinski et al. 2000). It ascribed, in part, to more mineral association and C protection at greater depths. Deep soils are more likely to be colder, waterlogged, anoxic, and nutrient-limited compared with surface horizons, leading to smaller and less active microbial communities. Environmental conditions in subsoils are typically more stable because they are buffered from rapid changes in moisture and temperature, and therefore provide a nutritionally and energetically impoverished but stable set of niches for microorganisms, compared with surface soils.

Greater amount of SOC accumulation and SOC sequestration in deep soil layer may be due to the three mechanisms: (a) Persistence of deep soil C, as it is bound to soil minerals and exists in forms that decomposers cannot access. The slow SOC decomposition at depth could result from inappropriate conditions for microbes, such as a lack of oxygen. In deep soil layers, fresh-C inputs by plants are extremely low; (b) Under these conditions, a new theory predicts that acquisition of energy from recalcitrant compounds cannot sustain microbial activity, and soil decomposition is strongly reduced. Biological and physical processes that bury recalcitrant SOC below the deposits of fresh C protect it from decomposition and allow C storage over a long time. The key factor in controlling C turnover in soils is accessibility (by microbes and exo-enzymes), which is restricted in deeper soil layers. This mechanism provides an interesting alternative to current approaches that involves short-term C storage in vulnerable compartments (plant biomass, surface SOC) (Dungait et al. 2012); (c) Even under favorable conditions of temperature and moisture for microbial activities, SOC from the deep soil does not provide enough energy to sustain active microbial populations and, thereby, the production of enzymes. The existence of this energetic barrier could reduce or cancel the effect of future changes in temperature on the decomposition of deep soil C pools, in contradiction to the predicted effect based on the temperature-induced acceleration of enzymatic reactions (Ghosh et al. 2018). We suggest that within the topsoil (0–30 cm), the process of aggregate formation is primarily influenced by vegetation type and root exudates. The soil aggregation is quite constant in similar type of soils with similar vegetation types, across the globe, thus having comparable potential of SOC sequestration. At lower depths (below 30 cm depth), SOC is increasingly associated with smaller aggregate sizes. In clay-illuviated soils, the sub-soil mineral properties, such as clay content and chemical composition, play a stronger role in the aggregation process and exert a much stronger influence on the SOC sequestration process. Thus, with rising atmospheric CO_2 posing a threat to the global climate, it is important to understand the mechanisms of SOC storage and stabilization not only in surface layer but also in deep layers under different land use and management. It should be clearly indicated that SOC storage (i.e., an increase of soil organic carbon stocks) is distinct from SOC sequestration, as the latter signifies long-term sequestration in soil and a net removal of atmospheric CO_2 (Chenu et al. 2019).

4.4 Mechanisms of SOC Sequestration

Three main mechanisms of SOM stabilization have been proposed: (1) chemical stabilization, (2) physical protection, and (3) biochemical stabilization. For analyses, protected SOM pool is divided into three pools according to the three stabilization mechanisms described (Fig. 4.2). The three SOM pools are the silt- and

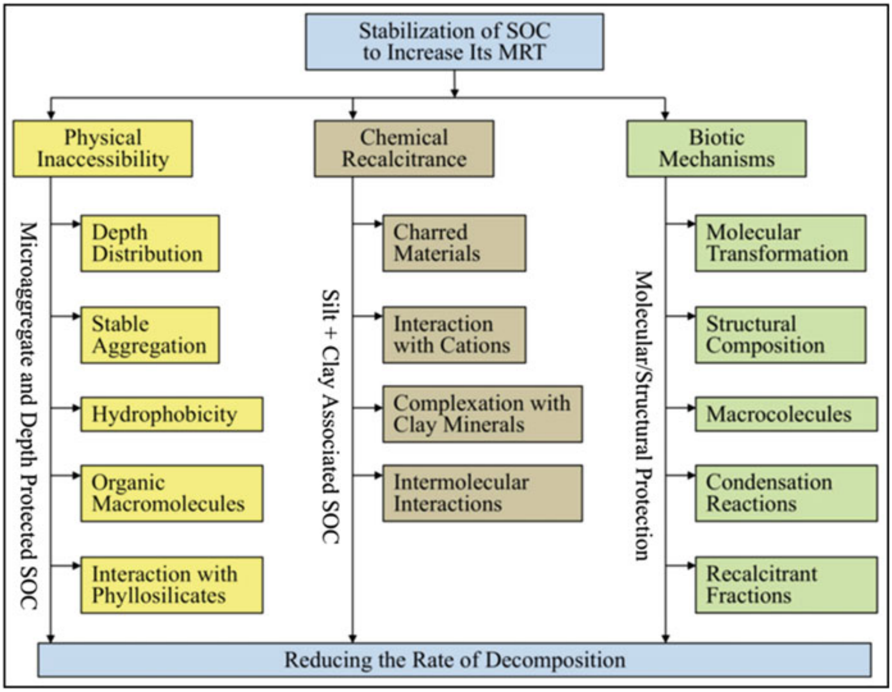

Fig. 4.2 Mechanisms of SOC sequestration (MRT: Mean residence time) (Source: Lal 2013)

clay-protected SOM (silt and clay defined as <53µm organo-mineral complexes), microaggregate protected SOM (microaggregates defined as 53–250µm aggregates), and biochemically protected SOM.

4.4.1 Chemical Stabilization

Chemical stabilization of SOM is understood to be the result of the chemical or physicochemical binding between SOM and soil minerals (i.e., clay and silt particles). There is a positive correlation between stabilization of SOC and silt plus clay content. In addition to the clay content, clay type (i.e., 2:1 versus 1:1 versus allophanic clay minerals) influences the stabilization of organic C. An enrichment of microbial products (i.e., amino sugars, carbohydrates, etc.) in the silt plus clay fraction under the no-till condition was reported along with better stabilization of SOC in silt plus clay (Hassink 1997). The silt- and clay-associated C forms a small fraction of the total C in soils. Consequently, sand-associated C accounts for the majority of total soil C. Given this dominance of sand-associated C and its greater sensitivity to cultivation than silt- and clay-associated C (Cambardella and Elliott 1992), in which C is transferred from the sand-associated fraction to the silt- and clay-associated fractions during decomposition, a loss of silt and clay-associated C upon cultivation is likely to be minimal. Hassink (1997) established a saturation level for silt and clay-associated C. In general, 2:1 clay minerals have a higher SOM binding potential than 1:1 clay minerals. Clay minerals with a high cation exchange capacity (CEC) and larger specific surface, such as montmorillonite and vermiculite, play much critical role in encapsulating SOM than clay minerals with a lower CEC and smaller specific surface, such as illite. On the other hand, kaolinite and especially Fe and Al-oxides have a high flocculation capacity due to electrostatic interactions through their positive charges. Aggregate stability increased to a maximum level with clay content and free Fe-oxides content.

4.4.2 Physical Stabilization

The physical protection exerted by macro- and/or microaggregates on particulate organic matter associated C (POM-C) is attributed to: (1) the compartmentalization of substrate and microbial biomass, (2) the reduced diffusion of oxygen into macro- and especially microaggregates which leads to a reduced activity within the aggregates, and (3) the compartmentalization of microbial biomass and microbial grazers. The compartmentalization between substrate and microbes by macro- and microaggregates is indicated by the highest abundance of microbes on the outer part of the aggregates and a substantial part of SOM being at the center of the aggregates. Higher loss of amino acids occurs by respiration from the aggregate surfaces than from within aggregates. The rate of glucose utilization decreased with depth into the aggregate. The inaccessibility of substrate for microbes within aggregates is due to pore size exclusion and related to the water-filled porosity (Killham et al. 1993).

Cultivation causes a release of C by breaking up the aggregate structures, thereby increasing availability of C. More specifically, cultivation leads to a loss of C-rich macroaggregates and an increase of C-depleted microaggregates. The inclusion of SOM in aggregates also leads to a qualitative change of SOM. For example, Golchin et al. (1994) reported significant differences in chemical structure between the free and occluded (i.e., within aggregates) light fraction. The occluded light fraction had higher C and N concentrations than the free light fraction and contained more alkyl C (i.e., long chains of C compounds such as fatty acids, lipids, cutin acids, proteins, and peptides) and less O-alkyl C (e.g., carbohydrates and polysaccharides). These data suggest that during the occlusion of free SOM into intra-aggregate light fraction, there is a selective decomposition of easily decomposable carbohydrates (i.e., O-alkyl C) and preservation of recalcitrant long chained C (i.e., alkyl C). Cultivation decreased the O-alkyl content of the occluded SOM. They suggested that this difference is a result of the continuous disruption of aggregates, which leads to a faster mineralization of SOM and a preferential loss of readily available O-alkyl C. Hence, the enhanced SOM protection by aggregates in less disturbed soil results in an accumulation of more labile C. Though the incorporation of POM into microaggregates (versus bonding to clay surfaces; i.e., chemical mechanism) seems to be the main process for protection of POM, the clay content and type of soil exert an indirect influence on the protection of POM-C by affecting aggregate dynamics. Despite different mechanisms prevail in different soils types and mineralogy for stabilization of SOC, each individual soil seems to have a maximum level of aggregate stability. Since the physical protection of POM-C seems to be mostly determined by microaggregation, it is obvious that the maximum physical protection capacity for SOM is determined by the maximum microaggregation, which is in turn determined by clay content and clay type.

4.4.3 Biochemical Stabilization

Biochemical stabilization is understood as the stabilization of SOM due to its own chemical composition (e.g., recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes (e.g., condensation reactions) in soil. Biochemical stabilization of SOM needs to be considered to define the soil C-saturation level within a certain ecosystem. This complex chemical composition can be an inherent property of the plant material or be attained during decomposition through the condensation and complexation of decomposition residues, rendering them more resistant to subsequent decomposition. Biochemically stabilized pool is akin to that referred to as the “passive” SOM pool and its size has been equated to the non-hydrolyzable fraction. Using ^{14}C dating, it has been found that, in the surface soil layer, the non-hydrolyzable C is approximately 1300 years older than total soil C (Paul et al. 2001). Several studies have found that the non-hydrolyzable fraction in temperate soils includes very old C and acid hydrolysis removes proteins, nucleic acids, and polysaccharides, which are believed to be more chemically labile than other C compounds, such as aromatic humified components and wax-derived long chain aliphatics. The stabilization of this pool and consequent old age is probably predominantly the result of its biochemical composition.

4.5 Measurement of Soil Organic Carbon Sequestration

Soil organic carbon sequestration can be measured by measuring the changes in soil organic carbon over a time period. The Kyoto protocol suggested monitoring and verification of changes in SOC of some benchmark sites after every 5 years. But practically C sequestration, or rather detectable SOC sequestration needs much greater time to take place. If the increase in annual C input can be of 30% or higher than the initial amount, differences in SOC might be detected within 5 years. Nevertheless, this enormous increase in C input can only be expected in free air carbon dioxide enrichment (FACE) and some other experiments, not in normal arable ecosystems (Smith 2004). To measure the rate of SOC sequestration in a normal ecosystem, a longer interval (50–100 years) may be considered. One-meter soil depth should be considered for measurement of effective SOC sequestration (Lal 2010). Hamburg (2000) has given three general rules for adequacy of soil sampling, as following:

1. All soil horizons must be considered (mineral and organic).
2. Soils must be considered to at least a depth of 1 m or the top of the C horizon.
3. Measurements of soil bulk density and carbon concentrations must be from the same samples.

4.5.1 Determining Soil Organic Carbon

Two basic principles are involved in determination of total C in soils, viz. dry combustion and wet combustion. In both methods, the soil samples are combusted and the CO_2 evolved is measured through infra-red or thermal conductivity detection. Complete combustion of the sample depends on the temperature within the combustion furnace, generally held between 950 and 1200 °C. To obtain total soil carbon, i.e., both organic and inorganic in nature, the sample is packed in a tin foil without any pre-treatment and combusted. To obtain SOC, the samples are to be pre-treated with dilute HCl in a silver foil to wave off carbonates, air-dried, and then dry combusted in a CHNS analyzer. Wet combustion involves oxidizing SOC to CO_2 with a solution containing potassium dichromate ($K_2Cr_2O_7$), sulfuric acid (H_2SO_4), and phosphoric acid (H_3PO_4), following the reaction (Snyder and Trofymow 1984):

$$2Cr_2O^{-2}{}_7 + 3C^0 + 16H^+ = 4Cr^{3-} + 3CO_2 + 8H_2O$$

This often results in incomplete digestion and under estimation of SOC. On the other hand, reflectance spectroscopy provides a rapid and non-destructive method for SOC measurement based on diffusely reflected radiation (mid- and near-infrared range; MIR and NIR) of illuminated soil (McCarty et al. 2002). Laser-induced breakdown spectroscopy (LIBS) also has been used in recent years for determination of total soil C (Ebinger et al. 2003).

4.5.2 Calculating Soil Organic Carbon Sequestration

Total SOC concentrations as determined through C analyzers can be converted to total C stocks of respective soil layers, by multiplying with the bulk density (BD) of these layers using the following equation:

$$\text{Total C stock of a soil depth}\left(\text{Mg ha}^{-1}\right) = \text{Total SOC concentration}\left(\text{g kg}^{-1}\right) \times \text{BD}\left(\text{Mg m}^{-3}\right) \times \text{depth (m)} \times 10$$

Carbon sequestration can be calculated by subtracting the initial SOC before the concerned interval from the final SOC stock:

$$\text{Carbon sequestration}\left(\text{Mg ha}^{-1}\right) = \text{SOC}_{\text{final}}\text{-SOC}_{\text{initial}}$$

The rate of sequestration can be termed as carbon sequestration potential (CSP) and calculated as:

$$\text{CSP}\left(\text{Mg ha}^{-1}\text{year}^{-1}\right) = \frac{\left(\text{SOC}_{\text{final}}\text{-SOC}_{\text{initial}}\right)}{\text{Number of years of experimentation}}$$

The amount of SOC remained and stabilized in the entire soil profile can be estimated as:

$$\text{SOC stabilisation (\%)} = \frac{\text{CSP} \times 100}{\text{ECI}}$$

where ECI is the estimated amount of C (Mg C ha^{-1} year^{-1}) input through crop residues, applied manure, and other carbon sources (Bhattacharyya et al. 2009).

4.5.3 Correction for Soil Mass

The above-mentioned calculations are often believed to be inadequate in comparing differing treatments comprised of different levels of mechanical disturbance and plant residue retention, because these practices often cause significant changes in soil bulk density (BD), changing in turn the mass of soil present in the concerned soil layer. So comparing total C stock on volumetric basis among treatments with different soil masses might result in an unequal basis leading to substantial error, as the total SOC would be over-estimated in the soil with greater BD relative to the soil with lesser BD. Therefore, calculation of SOC on equivalent soil mass (ESM) basis is more scientifically sound approach. The ESM can be calculated using the following formula (Dey et al. 2020):

$$\text{ESM}\left(\text{Mg ha}^{-1}\right) = \text{Initial BD}\left(\text{Mg m}^{-3}\right) \times \text{depth}\,(\text{m}) \times 1000\left(\text{m}^{2}\right)$$

To correct for the errors, the difference in the values of stored C in present soil mass of the concerned layer and that in the ESM is calculated.

$$\text{Error term} = \text{Total SOC concentration}\left(\text{g kg}^{-1}\right) \times \left(\text{M}_{\text{soil-ESM}}\right) \times 10$$

where M_{soil} is the soil mass and ESM is the equivalent soil mass. Both these terms are expressed in Mg m^{-2}. The calculations are as follows:

$$\text{ESM}\left(\text{Mg m}^{-2}\right) = \text{Initial BD}\left(\text{Mg m}^{-3}\right) \times \text{depth}\,(\text{m})$$

$$\text{M}_{\text{soil}}\left(\text{M gm}^{-2}\right) = \text{BD}\left(\text{Mgm}^{-3}\right) \times \text{depth}\,(\text{m})$$

This error term can then be deducted from the C content on a depth basis to obtain C on ESM basis through the following formula:

$$\begin{aligned} &\text{Total SOC on ESM basis}\left(\text{Mg ha}^{-1}\right) \\ &= \left[\left\{\text{Total SOC concentration}\left(\text{g kg}^{-1}\right) \times \text{BD}\left(\text{Mg m}^{-3}\right)\right.\right. \\ &\quad \times \text{depth}\,(\text{m})\big\}\text{-Total SOC concentration}\left(\text{g kg}^{-1}\right) \\ &\quad \times \left\{\text{M}_{\text{soil}}\left(\text{Mg m}^{-2}\right) - \text{ESM}\left(\text{Mg m}^{-2}\right)\right\}\big] \times 10 \end{aligned}$$

4.5.4 Correction for Sand Particles and Light Fraction

When studying SOM associated with soil aggregates, the correction factor for sand should be considered. Most free SOM is usually undercomposed debris that floats in heavy liquids and is referred to as light fraction. It is the material floating at densities ranging from 1.0 to 1.8 g cm^{-3} (Elliott et al. 1991). These particles may be associated with a particular size class of aggregates, but are not actually contained within aggregates. Contrarily, many aggregate size classes have the same size range as sand (0.05–2.0 mm), resulting inclusion of sand particles in aggregate separates. Since sand does not contain organic matter, it may dilute the organic matter content of aggregate fractions. To make an appropriate comparison of aggregate associated SOC, it is necessary to correct for the differing amounts of sand and undercomposed particulate material in the different size classes of aggregates (Elliot et al. 1991). The sand content of the physically fractionated aggregates was determined through dispersion with hexametaphosphate followed by sieving through a 0.053-mm sieve. Light fraction in these separates can be determined using sodium metatungstate (Oades 1988). Following formulas can be used for these corrections:

$$\text{Aggregated associated SOC} = \text{total aggregate associated C} - \text{light fraction associated C}$$

$$\text{Sand free SOC} = \frac{\text{Aggregate associated SOC}}{\text{1-Sand proportion}}$$

4.5.5 Correction for Gravel and Rocks

Soil organic carbon stocks are often misinterpreted in gravelly soils. The SOC is usually determined in fine soil (<2 mm), considering coarse fragments (>2 mm) free of SOC, although this may not be completely true. Total SOC stocks are often overestimated by virtue of considering high bulk density of gravelly soils. Bulk density estimates should be corrected for the proportion of coarse fragments, even if those coarse fragments might store a certain amount of organic carbon, which might lead to slight underestimation of SOC stocks. As suggested by Poeplau et al. (2017), the mass and volume of rock fragments should be determined in the soil sample. Then the bulk density could be calculated as:

$$\text{Bulk density}_{\text{fine soil}} = \frac{\text{mass}_{\text{sample}} - \text{mass}_{\text{gravel}}}{\text{volume}_{\text{sample}} - \frac{\text{mass}_{\text{gravel}}}{\text{density}_{\text{gravel}}}}$$

where $\text{density}_{\text{gravel}}$ is assumed 2.6 Mg m^{-3}. Considering the bulk density of fine soil, SOC stock can be calculated by the following formula:

$$\text{SOC stock of fine soil} = \text{SOC concentration of fine soil} \times \text{Bulk density of fine soil} \times \text{soil depth} \times (\text{1-gravel fraction}).$$

4.6 Strategies for Soil Organic Carbon Sequestration

Soil organic carbon reflects the net balance of organic C inputs and losses. Therefore, agricultural management practices that increase C inputs through increasing crop productivity, or through the application of external sources of C (e.g., animal manure, compost, and biosolids), and/or reduce C losses can increase soil C storage (Fig. 4.3).

Some important strategies pertinent to Indian conditions are summarized below:

Fig. 4.3 Outline of strategies for SOC sequestration (Source: Lal 2013)

4.6.1 Integrated Nutrient Management

Integrated nutrient management (INM) is application of organic materials along with mineral fertilizers to meet the crop nutrient demands. Studies under All India Coordinated Project on Long-Term Fertilizer Experiment showed continuous application of balanced fertilizer doses and farmyard manure (NPK + FYM) resulted in ~15, 19, and 24% higher SOC stock than NPK addition in the 0–15, 15–30, and 60–90 cm soil layers, respectively. Under NPK + FYM, higher SOC sequestration rate over unfertilized control plots (~745 kg ha^{-1} $year^{-1}$) were also observed (Ghosh et al. 2018) (Table 4.1). The additional C inputs through manures, increased roots, and root exudates under INM generally increase aggregate stability. Free primary particles form microaggregates through binding by persistent binding agents. Then labile binding agents bind microaggregates to form macroaggregates. Soil aggregation stabilizes SOC under INM against rapid mineralization by

Table 4.1 Total SOC stocks (t/ha) as affected by 44 years of intensive cropping and fertilization practices in north-western Indo Gangetic Plains (Source: Ghosh et al. 2018)

	Total SOC stocks (t/ha)			
Treatments	0–15 cm	15–30 cm	30–60 cm	60–90 cm
Control	7.69d	5.06d	9.50d	8.72c
N	9.30c	6.14cd	11.32c	9.54c
NP	8.91cd	7.65bcd	14.55b	11.06b
NPK	14.59b	9.13abc	18.45ab	12.10b
150%NPK	15.48ab	10.01ab	20.62a	14.67a
NPK + FYM	16.77a	10.91a	21.08a	15.02a

Values within a column followed by the same letter are not significantly different at $P \leq 0.05$

occluding it, making it inaccessible to microorganisms. Thus, soil aggregates favor physical entrapment of C (within macro- and micro-aggregates), chemical protection (through organo-mineral complexes, adsorption, etc.), biological stabilization (by recalcitrance transformation and condensation reactions within aggregates) under INM (Lal 2013). The macroaggregates contain microaggregates inside it and the SOC associated with these are reported to have high mean residence time. Many studies, including Ghosh et al. (2018) reported higher SOC within macro- and microaggregates under NPK+ FYM than unfertilized control and NPK alone. The readily metabolizable C and N in FYM and increasing root biomass and root exudates due to greater crop growth in NPK + FYM plots also aggravates soil microbial activity, as evident from microbial biomass carbon and enzymatic activities. Studies showed that FYM application increased lignin and lignin-like products, the main constituents of resistant C pools. Besides higher organics inputs, the greater amounts of recalcitrant C under NPK + FYM than NPK might be due to increased decomposition of labile compounds and accumulation of recalcitrant materials over time with NPK + FYM plots. Greater amount of SOC sequestration (~34%) occurred in deep soil layer under INM practices. Apart from inclusion of FYM as a direct source of SOM, INM promotes crop biomass development. This has a positive effect on supply of fresh organic matter to soil. Over the years, the treatments with recommended balanced fertilizer (NPK and 150% NPK) resulted in higher crop productivity than NP or NK plots, in turn, generating higher root and stubble biomass and root exudates (Kundu et al. 2007). These carbon inputs ultimately result in SOC sequestration in profiles under balanced fertilizer application (NPK or 150% NPK) plots. Thus, SOC accumulation rates in NPK plots (over control plots) in the 0–90 cm soil profile were 529 kg ha^{-1} $year^{-1}$ (Ghosh et al. 2018).

4.6.2 Conservation Tillage and Conservation Agriculture

Conservation tillage is a tillage system that conserves soil water, reduces soil erosion, and leaves at least 30% of the soil surface covered with residues after a

Table 4.2 Soil organic carbon fractions (g kg^{-1}) as affected by continuous conventional vis-à-vis CA practices (Source: Dey et al. 2020)

Treatment	Very labile SOC		Labile SOC		Less labile SOC		Non-labile SOC	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
CT-CT	2.25	1.50	1.05	0.45	0.76	0.89	18.5	17.1
CT-ZT	2.35	1.30	1.09	0.25	1.21	0.90	19.3	21.2
ZT-ZT	3.50	1.52	2.26	1.21	1.10	0.73	18.8	21.7
ZT-ZT + R	3.84	2.27	2.52	1.15	1.30	0.70	19.9	24.0
PB-PB + R	2.61	1.45	1.84	0.65	1.00	0.79	20.0	23.3
LSD ($p < 0.05$)	0.40	0.31	0.50	0.25	0.32	NS	1.77	NS

main crop is planted. Conservation agriculture (CA), on the other hand, is a production system involving minimum soil disturbance, soil cover through crop residues or other cover crops and crop rotations for achieving high productivity, with most efficient resource use (Kassam and Friedrich 2009). Tillage intensity is one of the most important agricultural management practices, which affects C levels in soil, more so in tropical Indian soils because they generally contain less C (<0.5%). Tillage has been shown to disproportionately affect the more labile forms of SOC (Table 4.2) (Dey et al. 2020). The conversion of natural to agricultural ecosystems and increased tillage intensity deplete the SOC pool and exacerbate the emission of GHGs (Lal 2013). Loss of SOC by cultivation can be mitigated by eliminating tillage, retention of vegetative soil cover, or by increasing the amount of non-harvested carbon returned to soil. A reduction in the disruption of soil macroaggregates under zero tillage (ZT) causes slower macroaggregate turnover. This in turn favors formation of "microaggregates within macroaggregates" around fine intra-aggregate particulate organic matter (POM), which are more stable in nature. With conservation tillage even without varying the crop residue input, an improvement in SOC can be obtained (Dey et al. 2020).

A greater SOC accumulation between and within the aggregates occurs, due to significantly higher POM-associated SOC under CA than conventional practices (Dey et al. 2016). Continuous supply of crop residues on the soil surface in CA creates a favorable environment for C cycling and formation of macroaggregates. Furthermore, the POM-C acts as a cementing agent to stabilize macroaggregates and protect intra-aggregate C in the form of POM. The products released by decomposition and root exudation processes enhance the aggregation of clay and silt particles and formation of temporary binding agents (i.e., fungal hyphae) that ultimately increase macroaggregation. The CA practices on the other hand, shows significantly lesser degree of C emission potential. Bhattacharyya et al. (2015) reported that a rice–wheat–mungbean system under CA emits ~1.86 t CO_2-C/ha/year lesser than its conventional counterparts. Thus, CA adoption is a novel climate smart agriculture technique that decreases GHG emissions and increases carbon sequestration potential of a soil.

4.6.3 Crop Diversification

As already discussed, the residue retention of legume crops in CA enhances SOC sequestration rates. Inclusion of leaf shedding legume or pulse crops in intensive cereal–cereal cropping systems, without changing tillage or fertilization also showed prominent improvement in SOC sequestration potential. The inclusion of chickpea in rice–wheat and maize–wheat system was reported to improve the total SOC in the surface soil by ~7 and 13%, respectively (Ghosh et al. 2019). Inclusion of chickpea in cereal–cereal rotation results in higher belowground biomass, leaf fall, and higher rhizodeposition, which can be termed as "legume effect" and has a critical role to play in build-up of SOC. Further, a considerable portion of legume roots (43–47%) are non-decomposable that finally contributes to SOC build-up. Both active/labile and passive/recalcitrant SOC pools can be increased through inclusion of legume, but the improvement is more on the active pools of SOC, thus increasing the lability of SOC (Jat et al. 2019).

4.6.4 Agroforestry

Agroforestry refers to the practice of purposeful growing of trees and crops and/or animals, in interacting combinations. Agroforestry systems are recognized as an integrated approach for sustainable land use aside from their contribution to climate change adaptation and mitigation. Numerous agroforestry systems are especially important in the Indian sub-tropics because of favorable climatic conditions and various socio-economic factors. Agroforestry has been recognized as having the greatest potential for C sequestration of all the land uses (IPCC 2015). Growing agroforestry biomass for bio-power and bio-fuels, and thereby replacing fossil fuel, has the potential to reduce increased atmospheric CO_2 (Jose and Bardhan 2012). The potential of agroforestry systems for C sequestration depends on the biologically mediated uptake and conversion of CO_2 into inert, long-lived, C-containing materials, a process, which is called bio-sequestration (Lorenz and Lal 2014). Bio-sequestration temporarily removes C from active cycling. Some SOC in agroforestry systems may persist for millennia indicating that terrestrial sequestration for climate change mitigation occurs particularly by avoided net SOC losses and the slowly on-going accumulation of the slowest SOC pool. Carbon sequestration in agroforestry systems occurs in aboveground biomass, i.e., stem, branch, and foliage, and in belowground biomass, i.e., roots, and in soil. Especially, the large volume of aboveground biomass and deep-root systems of trees in agroforestry systems have received increased attention for climate change adaption and mitigation. Global estimates for the C sequestration potential of agroforestry systems over a 50-year period range between 1.1 and 2.2 Pg C year^{-1} (Nair 2012). Compared to monocultures, agroforestry systems are more efficient in capturing the resources available at the site for biomass growth and the increased growth may result in higher C inputs to the soil. Also, direct C inputs to the soil can potentially be increased by some agroforestry practices. These include: (a) returning prunings of woody species to the soil as mulch and allowing abundant tree litter to decompose on site, (b) allowing livestock to graze and add dung to the soil, (c) allowing woody species to grow and add surface and belowground litter during crop fallow phases, (d) integrating trees and their litter input in animal production systems, (e) allowing litter inputs to the soil from shade-tolerant species growing under trees, and (f) benefiting from the soil C inputs of agricultural crops grown during early stages of the establishment of forestry plantations. The major reasons for the positive effects of trees on SOC sequestration are: trees modify the quality and quantity of belowground litter C inputs, and modify microclimatic conditions, such as soil moisture and temperature regimes (Laganière et al. 2010). Root litter usually decomposes more slowly than leaf litter of the same species. The root-derived C inputs are critical sources for the SOC pool in deeper soil horizons (Kell 2011). Trees have a higher potential for SOC sequestration than crop and pasture plant species, as trees may be associated with higher proportions of stabilized SOC in deeper mineral soil horizons. Specifically, root-derived C is more likely to be stabilized in the soil by physicochemical interactions with soil particles than shoot-derived C (Rasse et al. 2005). Furthermore, higher species richness and tree density can result in larger SOC contents in agroforestry systems (Saha et al. 2009). Similarly, mixed plantings with N fixing trees may cause higher biomass production and, thus, SOC sequestration and pools particularly in deeper soil horizons as N may promote humification rather than decay. However, the SOC and N interactions under agroforestry systems in surface versus deep soils are not entirely understood.

The management of agroforestry systems for SOC sequestration includes the selection of tree species and their silvicultural management, such as stand density and rotation length (Nair 2012). Functionally important tree species, i.e., those having deep and extensive root systems to enhance C input into the soil may have a high potential to enhance SOC sequestration in agroforestry systems (Lorenz and Lal 2014). Broadleaf trees, in particular, have a larger and more deeply anchored root system, i.e., higher root biomass/aboveground biomass ratios than coniferous tree species. Thus, they generate higher SOC inputs from roots at soil depth (Laganière et al. 2010).

4.6.5 Prevention of Soil Erosion and Restoration of Degraded Lands

The potential of SOC sequestration also lies in restoration of degraded soils and ecosystems whose resilience capacity is intact. The SOC is preferentially removed by wind- and water-borne sediments through erosional processes. Some of the SOC-enriched sediments are redistributed over the landscape, others are deposited in depressional sites, and some are carried into the aquatic ecosystems. A large quantity of this C is emitted into the atmosphere either as CO_2 by mineralization or as CH_4 by methanogenesis. Erosion-induced emission is reported to be 0.8–1.2 Gt C/year. By restoration of degraded lands, we can offset global warming due to atmospheric GHGs. Current estimates show that restoration of total eroded soils across the globe (1.1 billion ha) has a C sequestration potential of 0.2–0.4 Gt C year^{-1} (Lal 2013).

4.7 Conclusion

The SOC sequestration is a strategy to achieve food security through improvement in soil quality. Therefore, the adoption of best management practices and conversion of degraded lands to restorative land use is the need of the hour for enhancing C sequestration in soils. These practices include use of crop residues as surface mulch, adoption of complex crop rotations, conservation tillage and or conservation agriculture, diverse farming systems, use of INM strategies for recycling biosolids and other co-products, etc. There are numerous competing uses of crop residues, including production of cellulosic ethanol, co-combustion with coal or wood as biofuel, and use as animal feed, or an industrial raw material. Hence, policy interventions are required for using a part of crop residues for soil quality improvement that would reverse the trends of soil degradation, enhance the SOC pool, and improve environment. In this context, farming community should be properly guided and assisted for C farming and trading C credits. This requires organizing small-scale farmers into associations or producers cooperatives to reduce the transaction costs of C trading, monitoring and accounting. In addition, small-scale farmers can be successfully linked to larger farm enterprises, where transaction costs are reduced because of contract farming. Thus, policy interventions at regional, national, and international levels are required to promote the adoption of best management practices. Besides these, there are many on-going awareness programme promoting soil C sequestration to combat climate change (for eg. 4 per 1000 initiative). This aims in increasing SOC and is based on a blanket calculation of the whole global 2 m profile C stock, which amounts to an annual sequestration rate of 9.6 Gt C globally. India should take active part in 4 per 1000 initiative at government and farmers' levels. This would enhance soil/ecosystem/social resilience against climate disruption by increasing the terrestrial C pool, and improving the quality of soil, water, and natural resources. However, there are some challenges, viz., paucity of scientific data, finite capacity of soil carbon sinks, resource-poor marginal farmers, poor financial commitments, and improper implementation of C policies at grass root level. Hence, the need of the hour is that scientists, engineers, policy makers along with farmers should generate some innovative technologies that enhance below-ground C sequestration, which ultimately can make soil as a renewable as well as sustainable resource. Finally, the potential of SOC sequestration is finite in magnitude and duration. Therefore, it is high time to act on it with the hands in hand and cannot be afforded to ignore.

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5 Soil Biodiversity and Community Composition for Ecosystem Services

Ramesh Chandra

Abstract

Soil organisms are key component of ecosystems and provide several vital services to humans through their numerous functions. The magnitude of biodiversity in soil is several times greater than that present above ground. Microorganisms and fauna living in soils play central role in several ecological functions and processes such as formation of soil structure, cycling of carbon and nutrient elements, decomposition of plant and animal residues and inorganic soil pollutants and production of greenhouse gases. Besides, soil biodiversity also influences most of the critical services regulating an ecosystem, such as atmospheric composition and climate, water quantity and quality, pest and disease incidence in agricultural and natural ecosystems, and human and animal diseases. However, their roles were not recognized well in ecosystem functioning. Several evidences appeared suggesting that intensive agricultural practices as a result of green revolution technologies and anthropogenic activities have adverse impact on soil biodiversity. This generated global concerns to develop soil and crop management practices for protecting and maintaining soil biodiversity. The present communication describes the ecosystem services rendered by soil biodiversity and probable threats that harm soil biodiversity.

Keywords

Ecosystem Function · Community composition · Interactions · Global change · Land use · Management practices

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Biological diversity is the foundation for the maintenance of ecosystems. Consequently it is thought that anthropogenic activities that reduce the diversity in ecosystems threaten eco-system performance. A large proportion of the biodiversity within terrestrial ecosystems is hidden belowground in soils, and the impact of altering its diversity and composition on the performance of ecosystems is still poorly understood. Using a novel experimental system to alter levels of soil biodiversity and community composition, we found that reductions in the abundance and presence of soil organisms result in the decline of multiple ecosystem functions, including plant diversity and nutrient cycling and retention. This suggests that belowground biodiversity is a key resource for maintaining the functioning of ecosystem.

5.1 Introduction

Soil is a critical natural resource not only for agricultural production and food security, but also for the maintenance of most life processes and ecosystem. Soils contain enormous number of diverse living organisms assembled in complex and varied communities ranging from the myriad of invisible microbes, bacteria and fungi to the more familiar macrofauna such as earthworms, termites, enchytraeids, etc. The biodiversity in soils is several times higher than that above ground (Heywood 1995). However, the roles of soil biodiversity in ecosystem services are not well understood, as existing research has given emphasis mainly to assesses the effects of specific groups of organisms on some certain functions, while soil organisms interact within complex food webs, thereby influencing soil diversity (Hunt and Wall 2002). Soil is a source of diverse macro and microorganisms. Microbial community and species diversity in soil play significant roles in critical ecosystems functions and processes. This vast and hidden soil biodiversity contributes to the total terrestrial biomass, intimately linked to aboveground biodiversity (Wardleet al. 2004; Fierer et al. 2009) and contribute enormously to ecosystem. In recent years several studies have shown that anthropogenic activities, such as agricultural intensification and land use change have adverse impact on the microbial and faunal abundance and the overall diversity of soil organisms (Madar et al. 2002). This has prompted global concern that reduction in soil biodiversity may impair numerous ecosystem functions, such as nutrient cycling in soil and acquisition by plants coupled with cycling of resources between above- and belowground communities (van der Heijden et al. 2008; Wall et al. 2010). Therefore, soil biodiversity loss has attracted worldwide attention with increasing evidences that it may negatively affect ecosystem services on which society depends.

Microorganisms and fauna inhabiting soils play central role in various ecological functions and processes. Soil organisms influence many important ecosystem processes such as soil formation, organic residues decomposition and nutrient cycling, biological nitrogen fixation, carbon sequestration, water infiltration, purification and storage; improvement in soil physical conditions, suppression of pathogens and acting as an environmental buffer. It has been estimated that each g of soil may

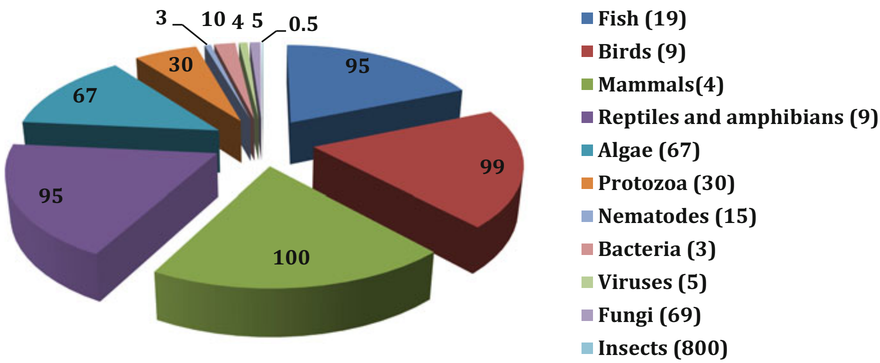

Fig. 5.1 Percentage of different described fauna and microbial species of world (Data in parenthesis are total number of described species in world $\times 10^3$) (Source: Hawksworth and Mound 1991)

contains up to 1 billion bacteria comprising of ten thousands of taxa, up to 200 m fungal hyphae, and a broad range of mites, nematodes, earthworms, and arthropods (Roesch et al. 2007; Bardgett 2005). However, our understanding of soil organisms and their functions is limited due to ignorance of soil biology by the microbiologist and ecologists. According to Hawksworth and Mound (1991), approximately only 10% of soil species have been identified so far (Fig. 5.1). Barring exception of earthworms and nitrogen-fixing bacteria, whose relationship to ecosystem function has been studied extensively, many aspects of other soil organisms have not been fully characterized for different ecosystems. However, this lack of knowledge does not undermine the importance of soil organisms in ecosystem functioning.

5.2 Soil Biodiversity and Ecosystem Services

Soil organisms provide many essential services to human beings through their multiple functions. Although most of these services do not have direct role in daily life of people, but indirectly responsible for providing important ecosystem services. These include nutrient cycling, soil formation and primary production. In addition, soil biodiversity influences most of the major regulatory services of an ecosystem, such as atmospheric composition and climate, water quantity and quality, pest and disease incidence in agricultural and natural ecosystems, and human diseases. Soil organisms may also control or reduce environmental pollution and contribute to other services that directly benefit people. For example, the genetic resources of soil microorganisms can be used for developing novel pharmaceuticals and genetically modified (GM) crops. The contributions of soil biodiversity for ecosystem services can be grouped under the following categories:

5.2.1 Soil Development

The role of organisms in soil formation and development has been well documented (Jenney 2009). They are one of the active factors of soil formation by contributing in decomposition processes of diverse plant and animal materials. Soil organisms contribute significantly to modifying the soil physical conditions by promoting soil aggregation, altering soil structure and creating new habitats. Soil organisms, particularly fungi, help in soil aggregation through production of polysaccharides, glomalins and lipids, while some species of filamentous fungi bind the soil particles (Chotte 2005). Bossuyt et al. (2001) have observed that the formation of macroaggregates (>2000μm) in an incubated soil with the addition of organic residues in the presence of a fungicide is significantly less than in the same soil without the fungicide. On the other hand, introducing a bactericide did not cause a reduction in the quantity of macroaggregates with respect to the control soil suggesting the role of fungi in aggregate formation. Fungi by way of binding soil particles also increase water infiltration and soil water holding capacity (Ritz et al. 2004). Bacterial activities in soil enhance disintegration of rocks and minerals and alter soil texture and structure. They also help to improve the strength of soil particles and soil resilience against soil runoff and soil erosion. Earthworms by virtue of their decomposing activities of dead organic matter have significant impact on transformation of soil structure, aggregate stability, soil colour, etc. (Edwards 2000). Earthworms being motile organism, substantially create, inhabit and burrow the soil particles for soil developments (Smith et al. 2008). Jongmans et al. (2003) noted that earthworms essentially change soil structure by casting and burrowing and as such improve soil aggregate stability, cohesion and adhesion in soil and pore-size division. Mites and collembola are known to fragment organic matter as they feed on soil microflora. This fragmentation to finer particles creates new surface areas for microbial colonization and consequently speeds up the decomposition and mineralization processes. Soil protozoa and nematodes help in the decomposition processes of soil organic matter (Darbyshire 1994). Termites play an important role in modifying the soil particles into fine and stable aggregate. Termites also regulate other components of soil biota, and increase soil water infiltration rate. The significance of soil fauna in altering soil physical properties depends on body size and generally increases with increasing body sizes. Thus, soil macrofauna, such as earthworms, ants, and termites have tremendous effects on soil porosity through creation of macropores and tunnels that permit greater water flow into the soil profile.

5.2.2 Organic Matter Recycling and Nutrient Availability

Soil organisms are responsible for the turnover of organic matter and the transformation of mineral nutrients in soil. Most plant nutrients such as N, P and S in soil are bound in organic molecules in organic matter and are unavailable for plants. Plants are dependent on the activities of soil microbes such as bacteria and fungi for acquiring these nutrients. These microorganisms have capabilities to mineralize organic forms of N, P and S in soil through secretions of extracellular enzymes. The nutrients immobilized in microbial cells are subsequently released, either through turnover and cell lysis, or via protozoic predation (Bonkowski 2004; Richardson et al. 2009). This liberates inorganic N, P and S forms into the soil, including ionic species such as ammonium, nitrate, phosphate and sulphate that are the preferred nutrient forms for plants (van der Heijden et al. 2008). The other important role of soil biota in soil fertility is through symbiotic association between plants and mycorrhizal fungi and biological nitrogen fixation. It has been shown that increasing the diversity of mycorrhizal fungi in soil can enhance plant productivity, quite possibly through improved nutrient acquisition (van der Heijden et al. 1998). Biological nitrogen fixation has been recently estimated to contribute 50–70 Tg N annually in the global agricultural system (Herridge et al. 2008). The residual soil organic matter forms humus, which serves as the central driver of soil quality and fertility. Thus, soil organisms indirectly support the quality and abundance of plant primary production (Wardle et al. 2004). It is worth mentioning that soil organic matter can be converted as humus only by the variety of soil organisms that exists in soils. It is an established fact that impairment in soil organic matter recycling and humus synthesis drastically reduces the fertility and adversely influences the plants and their products, including the supply of food, energy and nutrients. This service is critical in all ecosystems, including agriculture and forestry. Plant biomass production also contributes to the water cycle and local climate regulation, through evapotranspiration.

5.2.3 Carbon Cycle and Climate Control

Soil organic C pool is the second largest carbon pool on the planet and serves important ecosystem function of soils. Storage of carbon in soil gained increasing attention in recent years because changes in soil C have great bearing on climate change and global warming. Soil contains more carbon (at least 1500–2400 Pg C) than the atmosphere (590 Pg C) and terrestrial vegetation (350–550 Pg C) (Ciais and Sabine 2013). An increase in soil carbon storage can reduce atmospheric CO_2 concentrations. Green plants and photo- and chemoautotrophic microbes are pivotal in transferring atmospheric carbon in to soil (Lu and Conrad 2005; Trumbore 2006) through synthesizing organic compounds. Soil organisms also increase the soil organic carbon pool through the decomposition of dead biomass. The vast majority of soil microorganisms are heterotrophs that rely on organic matter for energy and nutrients. These soil microorganisms also release the soil carbon to the atmosphere through respiration of both autotrophic and heterotrophic organisms (Trumbore 2006) and as methane through action of methanogeneic bacteria under flooded soils. Since soil carbon plays vital role in various soil properties for maintaining soil quality, building soil carbon contents is considered one of the most powerful tools in climate change mitigation policy. Therefore, besides reducing the use of fossil fuels, planting trees is usually advised to control global warming through CO_2

fixation by accumulating and enhancing more organic carbon in the soil. According to Maron et al. (2018), carbon cycling in soil is highly vulnerable to microbial diversity changes mainly due to the fact that a decrease of soil microbial diversity affects the decomposition of both autochthonous and allochthonous carbon sources. It may decrease global CO_2 emission by up to 40% because of changing the source of CO_2 emission toward preferential decomposition of allochthonous C-substrates. The loss of soil biodiversity is therefore expected to reduce the ability of soils to regulate the composition of the atmosphere, as well as the role of soils in counteracting global warming. Anthropogenic activities also contribute to production of nitrous oxide, another greenhouse gas, which is 300 times more harmful in destroying the ozone layer, however, certain microorganisms, called denitrifying bacteria, convert nitrous oxide into inert nitrogen gas and helpful in mitigation of global warming (Willey et al. 2009).

5.2.4 Regulation of the Water Cycle

The water cycle includes the processes of evaporation, transpiration, condensation, precipitation and collection. Water is essentially required to support biodiversity and unavailability of sufficient water stresses on different organisms to varying extent causing biodiversity losses. On the other hand, biodiversity is critical to the maintenance of both the quality and quantity of water supplies in an ecosystem. The water cycle is influenced heavily by ecosystems and the life associated with them. Soil ecosystem affects the infiltration and partitioning of water in the soil, by creating soil aggregates and pore spaces. Adhesive polysaccharides substances produced by bacteria and thread-like hyphae produced by fungi bind soil particles into stable aggregates and reduce potential soil losses through erosion (Gupta and Germida 1988). Soil microfauna such as enchytraeidae (van Vliet et al. 1995) and earthworms (Edwards and Bohlen 1996) create burrows for facilitating water infiltration and improve aeration. Enchytraeids have been found to have more pronounced influence on soil structure in agriculture fields than in forest areas (Van Vliet et al. (1995). It has been observed that the reduction of earthworm populations due to soil contamination can reduce the water infiltration rate significantly (Edwards and Bohlen 1996). Soil biodiversity may also indirectly affect water infiltration, by influencing the composition and density of the vegetation, which in turn influence the structure and composition of litter fall and soil structure by rooting patterns. The diversity of microorganisms in the soil contributes to water purification, nutrient removal, biodegradation of contaminants and source of pathogenic microbes. Plants also play a key role in the cycling of water between soil and atmosphere through their effects on evapotranspiration. The loss of this service will have definite influence on quality and quantity of ground and surface water and nutrients. A reduction in microbial activity in soil will have negative impact on degradation of various soil pollutants, such as pesticides and industrial wastes. On the other hand increase in surface runoff will increase chances of soil erosion and floods in plains and landslide in hilly regions. Such deviations in water cycle will have substantial costs to the economy for building and operating more water purification plants and to take measures for controlling erosion and floods.

5.2.5 Soil Bioremediation

Bioremediation refers to the process of detoxification of soil pollutants through biological mean to a harmless state or below the permissible concentration limits. Soil biota play a key role in bioremediation by accumulating pollutants in their bodies, degrading pollutants into smaller, non-toxic molecules, or modifying those pollutants into useful products (Abatenh et al. 2017). Bacteria, archaea and fungi are major bioremediator showing to their nutritional versatility. Microorganisms have unique ability to convert, modify and utilize toxic pollutants for obtaining energy and their biomass production (Strong and Burgess 2008; Rakshit and Ghosh 2009). These services of soil organisms are continuously operating in soil and can be further accelerated by promoting microbial activity. Slater and Lovatt (1984) indicated that mixed microbial communities are more efficient in mineralizing some pollutants, such as chlorinated aromatic hydrocarbons and alkylbenzene sulphonates, than individual species. The microbes may not directly assimilate pollutants sometimes; they can be metabolized by the process of co-metabolism and transformed by other populations. The extracellular microbial enzymes belonging to the groups of oxidoreductases, hydrolases, lyases, transferases, isomerases and ligases mediate the metabolic reactions associated with bioremediation. Some of these enzymes have remarkable degradation ability due to their non-specific and specific substrate utilization. These microbial enzymes attack the pollutants and convert them to non-toxic products. Since microbial activities depend on environmental conditions, therefore microbial bioremediation technology requires optimization of environmental parameters to allow microbial growth and degradation to proceed (Kumar et al. 2011). Recently, genetically engineered microorganisms (GEMs) have shown increased potential for bioremediation applications in soil, groundwater and activated sludge environments and can be used effectively for biodegradation purpose (Kulshreshtha 2013). Phytoremediation, which is indirectly mediated by plants, is also useful to remove persistent pollutants and heavy metals from soil. Phytoremediation is particularly useful for in situ cleaning of pollutants from soils. The ability of plants to absorb and metabolize pollutants is well documented (Strong and Burgess 2008). Plants can accumulate various pollutants in their vegetative parts, making it possible to harvest the plants and dispose of them through the use of other treatment technologies. Microbial remediation differs from phytoremediation in the sense that it converts the pollutant in to non-toxic products instead of accumulating it in body tissue. Microbial bioremediation is a relatively low-cost and eco-friendly option for the removal or decreasing the concentration of a wide variety of pollutants and yielding non-toxic residues. It has been found that population of microorganisms associated with bioremediation increase in presence of pollutants and declines when the concentration of the contaminant drops. However, to date, microbial biodegradation is limited to those compounds that are biodegradable and there are concerns that some time products of biodegradation may be more persistent or toxic than the original pollutant compound. Therefore, bioremediation cannot be applied to all contaminants for a long-term solution.

5.2.6 Pest Control

Pests are integral part of crop production system and efficient pest control is essential for obtaining optimum production. Soil biodiversity is helpful in controlling the various pests by acting directly on soil inhabiting pests and indirectly on aboveground pests. Pest infestations generally occur in absence of efficient natural control by soil fauna. An ecosystem offering a high biodiversity of soil organisms provides efficient natural control because of existence of higher probability of natural enemy of pests. Interestingly, in natural ecosystems, pests are involved in the regulation of biodiversity. The practice of controlling pests in natural or organic farming crops relies on enhancement in the population of natural predation instead of chemicals. This farming approach gained much impetus to minimize the risks on human health, soil biodiversity and conserving natural resources such as water. In organic farming, insect pests are not destroyed, but instead their population is kept below threshold levels within a complex living and vibrant ecosystem. As an example, beetles Ladybird and Dragonflies are useful to eliminate aphids and mosquitoes, respectively. Microbial biocontrol agents comprising bacteria *Bacillus thuringiensis* (Bt) are effective for controlling butterfly caterpillars. This bacterium releases a potent toxin in the gut of insect pests larvae and kills them. In recent pasts, genes producing *Bacillus thuringiensis* toxin has been introduced into plants through genetic engineering for creating genetically modified (GM) crops. Bt cotton is one such example, which is being cultivated in some parts of our country. Another example of biological control being developed for use in the treatment of different plant disease is the fungus *Trichoderma* species. *Baculoviruses* are pathogens that attack insects and other arthropods. They have shown no negative impacts on plants, mammals, birds, fish or even on non-target insects. Production of antibiotics by soil bacteria is another indirect significant chemical defense strategy for controlling plant diseases. For example, some strains of fluorescent pseudomonads produce antibiotic phenazine, which is beneficial in controlling take-all in wheat caused by *Gaeumannomyces graminis* var. *tritici* (Ggt) (Brisbane and Rovira 1988). It has been experimentally found that when Tn5 mutants of such pseudomonads are introduced into the wheat rhizosphere, the removal of antibiotic production has been associated with reduced control of Ggt (Thomashow and Weller 1991). The presence of particular groups of organisms has been associated with the suppression of plant disease. Springtails *Proisotoma minuta* and *Onychiurus encarpatus* consume the soil borne fungal plant pathogen *Rhizoctonia solani* (Curl et al. 1988). Amoebae of the *Vampyrellidae* perforate conidia of *Cochliobolus sativus* on barley (Old 1967). Protozoa have been reported to play an active role in disease suppression by consuming pathogenic nematodes, bacteria and fungi (Zwart et al. 1994).

However, plant pathogens generally have rapid growth rates than protozoan predators, and therefore protozoa may not suppress plant pathogens completely in soil.

5.2.7 Human Health

Soil microorganisms are the important source of antagonistic activities. Several microorganisms are known to produce a wide variety of antibiotics, which are used for the control of numerous infections and diseases in humans, animals and crops. Antibiotics are produced by several groups of microorganisms such as bacteria, fungi and actinomycetes as their natural defense system against microbes living in the vicinity. Soils contain a large number diverse population of microorganisms. Owing to their vast diversity, they are an important source of various chemicals and genetic resources for the development of new pharmaceuticals. Many antibiotics being used currently have been originated from soil microorganisms. For example, penicillin isolated from the soil fungus *Penicillium notatum* by Alexander Fleming in 1928, and Streptomycin in 1944 by S. A. Waksman, which is produced by certain species of *Streptomyces*. Antibiotic production by soil bacteria, involving secondary metabolism, has been harnessed for decades for a wide range of medical applications. Soil microorganism had always been the primary source for production of antibiotics and still continues to maintain its significance. But indiscriminate use of antibiotics created another critical problem of multidrug resistance against pathogenic microbes. Since antibiotic resistance develops fast, the demand for new molecules is continuously increasing for the control of developing resistant microbial strains against existing antibiotics. Thus, loss of soil biodiversity would hamper capacity to develop novel antibiotic compounds.

5.3 Potential Threats to Soil Biodiversity

5.3.1 Soil Degradation

Soil organic matter (SOM) plays key role in maintaining soil quality and productivity. SOM serves as substrate for heterotopic soil microorganisms and directly impacts the diversity. Thus, loss of soil organic matter is one of the major causes impacting soil biodiversity. Several anthropogenic activities such as inappropriate agricultural practices, over-grazing, land clearing and forest fires result in depletion of soil organic matter and enhance the risk of loss in soil biodiversity. Therefore, strategies such as balanced fertilizer use and organic manure application, crop residue management, crop rotation, conservation tillage, erosion control, water management, use of soil amendments, etc. that help in improving soil SOM should be given top priority for soil biodiversity conservation. Besides, development of soil salinity due to faulty irrigation practices and soil compaction by excessive tillage using heavy farm implements under intensive cultivation are some other reasons of soil degradation. Several soil and crop management practices have been developed, standardized and recommended for avoiding soil degradation and maintaining soil health and sustaining productivity.

5.3.2 Inappropriate Soil and Crop Management Practices

Soil and crop management practices are being constantly evolved to increase productivity levels coupled with reduced consumption of energy and water. Alterations in crop management practices significantly influence structure and species composition of soil microbial community. These changes in native soil microbial community, though not yet understood properly, have been observed to play significant role for plant disease suppression (Mazzola 2004), inputs use efficiency, and soil quality and factor productivity (Jacoby et al. 2017). A large number of studies demonstrated that excessive tillage under intensive agriculture, monocropping and imbalance use of chemical fertilizers alone are known to adversely affect soil biological health and ecosystem functioning including biological nitrogen fixation and vesicular arbuscular (VA) mycorrhizal association (Chandra 2013). In contrast, farm practices such as intercropping, reduced tillage, crop rotation and land use intensification have a positive impact on soil microbial diversity (Van der Heijden and Wagg 2013).

5.3.3 Climate Change

Global climate change is already a well-known fact and it is expected to further increase atmosphere temperature of 0.2 °C per decade coupled with shift in the rate and intensity of rainfall. Climate change variables such as temperature, elevated CO_2 concentration and precipitation have direct impact on soil biodiversity through bringing change in quantity and quality of SOM, moisture content and nutrient availability. Kirschbaum et al. (1996) reported that SOM contents generally increase with soil water content and decrease with temperature. Net primary productivity (NPP) usually increases with increasing temperature and elevated atmospheric CO_2, leading to greater returns of carbon to soils, but increasing temperature accelerates decomposition at rates exceeding to NPP leading to reduction in SOM content. It has been reported that plants under elevated CO_2 decrease their allocation of N-rich metabolites and increase the allocation of C rich metabolites to root exudates (Tarnawski and Aragno 2006) and result an increase in microbial activity. Soil microorganisms are often carbon limited and therefore, increased carbon availability stimulates microbial growth and activity. It is generally assumed that the CO_2 induced increases in soil C availability will increase fungal biomass more than bacterial biomass (Hu et al. 2001). Since fungi play important roles in organic matter degradation, nutrient cycling, plant nutrition and soil aggregate formation, shifts in fungal communities might have a strong impact on soil biodiversity and functioning.

Bacteria and fungi serve as substrates for a multitude of tiny predators and grazers, including protozoa, nematodes and arthropods in soil. Therefore, an increase in bacterial growth due to an increasing C allocation at elevated atmospheric CO_2 levels may be followed by an increase in population of grazers, resulting in a higher turnover of the microbial biomass. It has been assumed that increased temperature caused microbes to undergo physiological changes that result in reduced carbon-use efficiency (Allison et al. 2010) or acclimatization of soil microbes to higher soil temperatures by adapting their metabolism. A great variability has been reported in the response of soil community function to climate change and the potential effects of these responses at the ecosystem level (Smith et al. 1998).

5.3.4 Soil Pollution

Soil pollution refers to the presence of xenobiotics (e.g. chemical compounds, radioactive elements) that are capable to bring changes in the soil chemical, physical and biological properties. Soil pollution arises due to application of toxic agro-chemicals and disposal of sewage sludge and industrial wastes in agriculture for supplying plant nutrients and irrigation. These pollutants indirectly affect soil services through contaminating the soil food web, and bring changes in the availability of soil organic matter and microbial diversity. Heavy metals are the most hazardous pollutants entering in soil through industrial wastes, sewage sludge and fertilizer application. Some heavy metals (e.g. Fe, Zn, Cu, Ni, Co) at low concentrations are vital for many microbial activities, being involved in the metabolism and redox processes. However, high concentrations of heavy metals usually have inhibitory or toxic effects on soil organisms (Bruins et al. 2000). Adverse effects of metals on soil microbes result in decreased decomposition of organic matter, reduced soil respiration, decreased diversity and declined activity of several soil enzymes (Tyler 1974). Rajapaksha et al. (2004) found that bacterial community is more sensitive to increased concentrations of heavy metals in soils than the fungal community and fungal/bacterial ratio increased with increasing metal levels. Xenobiotic characteristics of pesticides may also adversely affect the survival of beneficial soil microorganisms and their associations with plants such as N_2 fixation, P solubilization, nitrification, denitrification, ammonification, redox reactions, methanogenesis, etc. In contrast, few reports indicated positive effects of applied pesticides on soil health (Hussain et al. 2009). The impact of various soil pollutants is not uniform on different macro- and microorganisms, but differ with species, as well as on the dose and exposure time to the pollutant. Microorganisms have a very short generation time and may develop resistance to toxic chemicals at a faster rate. The sensitivity of nematodes to pentachlorophenol after 72 h of exposure was found 20 to 50 times higher than their sensitivity to cadmium. The toxic effect of xenobiotic on earthworms is highly dependent on their feeding habits and ability to consume specific pollutants (Turbe et al. 2010). Therefore, for each chemical pollutant and species considered, a specific dose–response curve should be determined. The detail information on the impacts of chemical pollutants on soil ecosystem functioning is still lacking particularly on ecological risk assessments. However, significant impacts of pollutants are expected on nutrient cycling, fertility, water regulation and pest control services.

5.3.5 GM Crops

Genetically modified (GM) crops may also appear as an upcoming source of pollution for soil organisms. Transgenic plants have been found to have significant effect on non-target soil microorganisms (Liu et al. 2005; Beura and Rakshit 2011). These crops may affect the soil microbial diversity directly by producing transgenic proteins and indirectly by mediating changes in plant proteins and root exudates composition. However, factors such as composition and content of transgenic proteins in GM plant, the resistance of the proteins to degradation, soil physical, chemical and biological environment influence the accumulation and bioavailability of the GM proteins in soil. Dunfield and Germida (2001) observed that variations in soil microbial communities due to transgenic canola were temporary and did not persist for long period. In contrast, Sarkar et al. (2009) in controlled pot studies found that Bt cotton had a positive effect on most of the microbial and biochemical indicators such as microbial biomass C, N and P, microbial quotient and a range of soil enzyme activities in comparison to non-Bt isoline even though organic carbon was similar. Most effects of GM crops have been observed on soil biodiversity by altering the structure of bacterial communities, bacterial genetic transformation, and the efficiency of microbial-mediated processes. The available information on the impact of GM crops on soil biodiversity and ecosystem services is not conclusive and suggests that GM crops may not necessarily affect soil biodiversity beyond a critical level and warrants in depth research.

5.3.6 Introduction of Exotic Species

Exotic species are called invasive when they become disproportionally abundant. Urbanization, land use change and climate change accelerate possibilities for species expansion and suggest that they will become a growing threat to soil biodiversity in the coming years. Invasive species can have major direct and indirect impacts on soil services and native biodiversity. Invasions of exotic plants have strong effects on aboveground plant community structure by providing fierce competition to eliminate native plant species and decrease community diversity. It has been observed that invasions of exotic plants influenced soil community structure, in such a manner that microbial community composition is more highly influenced than other aspects of microbial diversity (Swedo et al. 2008). Invasive plants may also alter nutrient dynamics and thus the abundance of microbial species in soil, especially of those requiring specific dependence such as mycorrhiza. Population of organisms playing role in biological processes usually reduce establishment of invasive species, particularly when they have species-specific relationships with plants. In turn, plant invasions may be favoured by the release of their soil pathogen and root-herbivore control in the introduced area. However, soil biodiversity may act as natural enemies against establishment of invasive plants.

5.4 Epilogue

Soil biological processes and soil biodiversity play pivotal role in ecosystem services such as nutrient cycling, soil formation and primary production. In addition, soil biodiversity influences most of the major regulatory services of an ecosystem. Soil organisms may also control or reduce environmental pollution and contribute to other services that directly benefit people. It has been indicated that modern agricultural practices are parallel with a decline in abundance and alter the composition of soil communities, which in turn will impact the ecological processes. The lack of awareness of the importance of soil biodiversity in society further aggravated the problem of the loss of ecosystem services due to loss of soil biodiversity. Therefore, an understanding of soil biodiversity is of paramount importance and requires immediate attention in order to maintain/improve ecosystem functioning. Our understanding of the links between soil biodiversity and soil functions is poor because measurement of all soil microorganisms is not easy. The recent advances in RNA extraction from soil might permit to determine active species in soil. The research priorities needed to address in future includes (1) assessment of the total genetic diversity of soil, (2) to establish the link between different soil species and/or communities and ecosystem functions, (3) to monitor changes in soil biodiversity due to agricultural practices and other perturbation, (4) identifying potential indicators of soil biodiversity and (5) to determine the impact of various soil and crop management practices on biodiversity, nutrient cycling, plant residue decomposition, pest populations, and their simultaneous impact on agricultural productivity.

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Rhizodeposition: An Unseen Teaser of Nature and Its Prospects in Nutrients Dynamics

6

Abhik Patra, Vinod Kumar Sharma, Arghya Chattopadhyay, Kiran Kumar Mohapatra, and Amitava Rakshit

Abstract

Rhizodeposition is defined as all root-derived compounds and plant materials that are released from living roots during plant growth. A wide range of organic compounds are involved in this process, including inorganic ions, sloughed cells, mucilages, exudates and root hairs. Rhizodeposition has diverse functions in plant nutrition and soil ecology, such as improving nutrient availability, acting as allelochemicals, and serving as a carbon and energy source for rhizosphere soil microorganisms. It is mainly quantified through tracer techniques like carbon tracer technique, labeling plants with N^{15} and dwell labeling technique but, scientific review suggested that cotton wick method is the best technique for quantification. The rhizodeposition plays a crucial role for the mobilization of plant nutrients and serves a complex mixture to carry out ecological functions in the soil. It has been extensively reported that plants invest a large portion of their photosynthetic carbon in the development and maintenance of the rhizosphere through rhizodeposits), which improves the ability to optimally exploit water and nutrient distributions in the soil. Concentration of rhizodeposits has direct effect on C and N mineralization. Different organic acids and phenolic compounds present in rhizodeposition help in increasing different exoenzymes activity,

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which ultimately increase the mineralization of native, applied and fixed nutrients in soil. Plant root secretes phytosiderophores which improve the micronutrients uptake in plant. In nut shell, through understanding the relationship between rhizodeposits and its function, the insight information of change in microbial diversity and different nutrients transformation process can better understand.

Keywords

Rhizodepositions · Allelochemicals · Tracer techniques · Exoenzymes activity

6.1 Introduction

In terrestrial ecosystems, plants are the key primary producers and use their complex root systems to exploit soils for resources. The soil environment influenced by roots is known as the rhizosphere and supports diverse microbial communities that are generally more densely populated than those in root-free soil (Dennis et al. 2008; Zhang et al. 2020). These relatively dense communities are supported by carbon-containing materials lost by roots (rhizodeposition) and have both direct and indirect effects on plant health and nutrition (Cambell and Greves 1990; Ho et al. 2017). Improved understanding of belowground plant–microbe interactions will facilitate development of improved management strategies for environment or commercial purposes. Rhizodeposits include a wide variety of compounds derived from sloughed-off root cells and tissues, mucilages and exudates originating from intact roots, and soluble lysates and volatile compounds released from damaged cells (Uren 2000; Dakora and Phillips 2002; Oburger and Jones 2018; Tian et al. 2020a, b). Most studies that investigate rhizosphere microbial community structure do not consider the composition of all rhizodeposits and focus instead on the soluble exudates. At maturity rhizodeposition can be twice as much as roots and represents a substantial energy transfer from plants to soil microorganisms (Gregory 2006). Rhizodeposition is defined as organic substances released from living roots into the soil during plant growth (Nguyen 2003) and contains a wide range of organic compounds (Gregory 2006; Fernández et al. 2020). Rhizodeposits include a wide variety of compounds derived from sloughed-off root cells and tissues, mucilages and exudates originating from intact roots, and soluble lysates and volatile compounds released from damaged cells (Dakora and Phillips 2002; Oburger and Jones 2018; Tian et al. 2020a, b). Rhizodeposition describes the carbon flux entering the soil from plant roots and is composed of several groups, distinguished by their mode of release, exudates, secretions, lysates, gases and mucilage. Rhizodeposition is the process of release of volatile, non-particular and particular compounds from living plant roots and these compounds contain a wide range of organic compounds (Gregory 2006). Uren (2000) describes rhizodeposition as the release of all kinds of compounds lost from living plant roots, including ions and volatile compounds. For practical reasons, collecting root rhizodeposits is usually done in hydroponic plant culture which favours the collection of only soluble exudates. In order to exploit rhizosphere interactions for environmental or commercial benefits, however, it is essential to understand how all plant-derived substrates influence soil microorganisms.

Estimates for the total allocation of photosynthates to roots range between 30% and 50% for pasture plants and 20% and 30% for cereals such as wheat and barley (Kuzyakov and Domanski 2000). For cereals, roughly half of this carbon remains in the roots, approximately one-third is released from the rhizosphere by root or microbial respiration within a few days, and the remaining fraction is incorporated into rhizosphere microbial biomass and soil organic matter (SOM) (Kuzyakov and Domanski 2000). Assuming that roots and microorganisms contribute equally to respiration in the rhizosphere (Kuzyakov 2006) rhizodeposition represents approximately 11% of net fixed carbon and 27% of carbon allocated to roots (Jones et al. 2009; Hirsch et al. 2013; Tian et al. 2020a, b). However, estimates of carbon economies within plants are controversial and vary considerably between different workers. Likewise, estimates for the relative sizes of various pools of rhizodeposits are uncertain. Root exudates are reported to comprise the largest fraction of non-volatile rhizodeposits (Meharg and Killham 1988), and of these, sugars and amino acids are thought to be released in the greatest quantities (Farrar et al. 2003). However, before analysis, rhizosphere solutions are often filtered, thereby removing sloughed-off cells and tissues despite their potential significance in the total rhizodeposition budget (Iijima et al. 2000). Many factors including space and time influence rhizodeposition quantitatively and qualitatively (Carvalhais et al. 2011). Rhizodeposition is increased by environmental stresses (e.g., phosphate or iron deficiency), microorganisms and the presence of solid rooting media. Despite this, most rhizosphere carbon flow research has been undertaken in sterile solution culture, which tends to exclude sloughed-off root cells and tissues and is not a realistic substitute for plants growing in soil (Mühling et al. 1993). Furthermore, studies on young roots through pulse-labeled C^{14} techniques showed that photosynthates partitioning to roots, rhizosphere respiration, and soil residues decreases with increasing plant age (28–600 days) by 43%, 28%, and 20%, respectively (Nguyen 2003; Stevenel et al. 2019; Tian et al. 2020a, b).

6.2 Rhizodeposition: An Outline

Rhizodeposition is defined as organic substances released from living roots into the soil during plant growth (Nguyen 2003) and contains a wide range of organic compounds (Gregory 2006; Fernández et al. 2020). Rhizodeposits include a wide variety of compounds derived from sloughed-off root cells and tissues, mucilages and exudates originating from intact roots, and soluble lysates and volatile compounds released from damaged cells (Dakora and Phillips 2002; Oburger and Jones 2018; Tian et al. 2020a, b). Rhizodeposition describes the carbon flux entering the soil from plant roots and is composed of several groups, distinguished by their mode of release, exudates, secretions, lysates, gases and mucilage. Rhizodeposition is the process of release of volatile, non-particular and particular compounds from living plant roots and these compounds contain a wide range of organic compounds

(Gregory 2006; Tian et al. 2020a, b). Uren (2000) describes rhizodeposition as the release of all kinds of compounds lost from living plant roots, including ions and volatile compounds. Inorganic ions might also be included in this term (Uren 2000). For practical reasons, collecting root rhizodeposits is usually done in hydroponic plant culture which favours the collection of only soluble exudates. In order to exploit rhizosphere interactions for environmental or commercial benefits, however, it is essential to understand how all plant-derived substrates influence soil microorganisms.

6.2.1 Compounds Present in Rhizodeposition and Their Functions

Rhizodeposits produced near the apical root zone or root cap and ingested mucilages, volatile, soluble lysates and exudates of polysaccharides (Hassan et al. 2019). Rhizodepositionally secreted organic molecules include sugars, amino acids, carboxylic acids, organic acids, enzymes, fatty acids, phytohormone and vitamins (Table 6.1) (Dennis et al. 2010; Yadav et al. 2015). Rhizodeposition regulates several ecological soil functions including nutrient availability and mobilization,

Table 6.1 Compounds present in rhizodeposition and their functions in plant growth and nutrition

Groups	Compounds	Functions
Sugars	Arabinose, fructose, galactose, glucose, maltose, oligosaccharides, raffinose, ribose, sucrose, xylose	Plant and microbial growth, nutrient source
Amino acids	α-Alanine, β-alanine, arginine, cystine, glutamic, glycine, histidine, isoleucine, lysine, methionine, mugineic, proline, serine, tryptophan, valine	Nutrient source, chemoattractant for microbes
Organic acids	Acetic, butyric, citric, p-coumaric, formic, glutaric, lactic, malic, oxalic, pyruvic, succinic, vanillic	Nutrient source, act as chelators, acidifiers of soil
Fatty acids	Linoleic, linolenic, oleic, palmitic, stearic	Plant and nutrient source microbial growth
Sterols	Campesterol, cholesterol, sitosterol, stigmasterol	Nutrient source
Vitamins	Biotin, choline, N-methyl nicotinic acid, niacin, thiamine, riboflavin, pyridoxine, pantothenate	Plant and microbial growth, nutrient source
Flavonones and nucleotides	Adenine, flavonone, guanine, uridine/cytidine	Chemoattractant for microbes, nod gene inducers. Nutrient source
Miscellaneous and inorganic compounds	Auxins, hydrocyanic acid, ethanol, inositol and myoinositol, dihydroquinone, alcohols, inorganic ions, and gaseous molecules	Control mitosis and gene expression, stimulate microbial growth, chemoattractant for microbes

soil aggregate formation, carbon sequestration and microbial community structuring (Hassan et al. 2019). Kuzyakov and Xu (2013) confirmed that rhizodeposits offer better soil microbes with energy for the solubilization of organic nitrogen and other nutrients in organic soil matter.

6.2.2 Factors Affecting Rhizodeposition

6.2.2.1 Abiotic Factors

Rhizodeposition is a highly variable process and quantity and quality are influenced by various abiotic factors such as drought, mechanical impedance, soil texture, anaerobic conditions, light intensity, day length, atmospheric CO_2 concentration, toxicity and nutrient deficiency (Fig. 6.1) (Marschner 1995; Nguyen 2003; Hassan et al. 2019). Soil texture and density influence rhizodeposition by altering the friction which influences the sloughing and thus the production of border cells which are released into the soil (Nguyen 2003; Hirte et al. 2018). It was observed that water stress had no major direct influence on deposition of N, but indirectly influenced

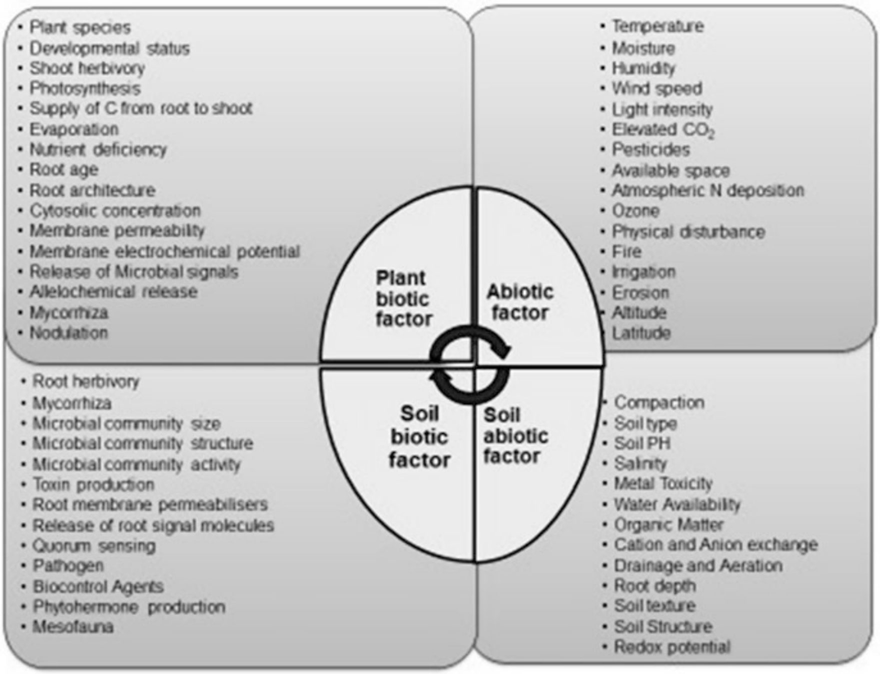

Fig. 6.1 Schematic representation of the biotic and abiotic factors of plant and soil that influence rhizodeposition

rhizodeposition due to reduced plant growth and nutrition (Janzen and Bruinsma 1993).

Rhizodeposition of C increased with increasing water stress (Martin 1977; Preece and Peñuelas 2016; Breitkreuz et al. 2020), which can be attributed to an increase in the deposition of mucilage, which has a high polysaccharide and therefore C content and a low N content (Janzen and Bruinsma 1993).

6.2.2.2 Biotic Factors

Biotic factors, such as plant species and variety, their physiological status, competition between individual plants, pathogen infection, soil microorganisms, symbiosis with rhizobia or mycorrhiza and N_2-fixation in legumes, have also been observed to influence rhizodeposition (Fig. 6.2) (Van Hecke et al. 2005; Fernández et al. 2020).

It has also been reported that rhizodeposition of C in dicotyledonous plants was higher than in monocotyledonous plants (Whipps 1987; Sharma et al. 2020). Plants with symbiotic N_2-fixation have a higher energy demand resulting in increasing CO_2-assimilation and root respiration (Merbach et al. 1999) and therefore contribute to a higher C rhizodeposition. In red and white clover (*Trifolium pratense* L. and *Trifolium repens* L.) 92 and 95% of plant N was derived from atmospheric N_2-fixation, resulting in the NdfR fraction being mostly N from atmospheric N_2-fixation (Høgh-Jensen and Schjørring 2001), which ultimately influence N rhizodeposition. Rhizodeposition also differed between plant species and variety (Table 6.2) because the production of border cells which contribute to rhizodeposition is to a certain extent genetically influenced (Nguyen 2003; Kuzyakov and Xu 2013; Fernández et al. 2020).

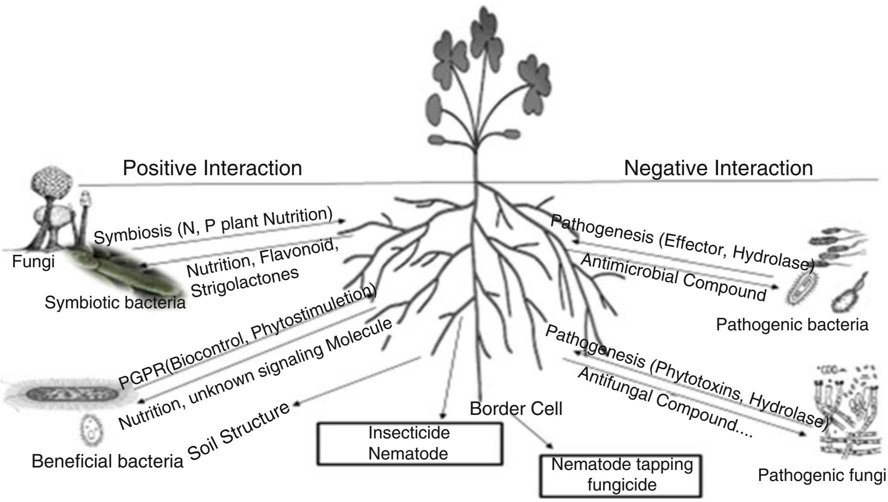

Fig. 6.2 Interactions between rhizodeposition and microorganisms

Table 6.2 Root hair length and diameter of maize and rhizodeposition amount (Nguyen and Henry 2002)

Root hair	Length (μm)	Diameter (μm)	Rhizodeposition (ng C mm^{-1} root)
Small hairs	80	5	2.2
Medium hairs	500	10	56
Large hairs	1500	20	680

6.2.3 Mechanisms of Release of Rhizodeposition

6.2.3.1 Sloughing-off of Root Border Cells

Apical meristems of plant roots are covered by a group of cells arranged in layers, the root cap, and the surface of which sloughs off as the root tip wends its way through the soil (Fig. 6.3) (Barlow 2002; Fustec et al. 2010; Hassan et al. 2019). In mature branched roots, the entire cap itself can be lost as the results of pathogen attacks or as part of a normal developmental process, as it was observed in field-grown maize (Varney and McCully 1991; Driouich et al. 2013). The cap initials generate cells that are displaced from the inner zone towards the periphery of the cap where they slough off. During their transit through the cap, the cells first differentiate into statocytes, i.e., gravity-perceiving cells, and then into cells able to secrete mucilage (Waisel et al. 1991; Canellas and Olivares 2017; Hirte et al. 2018). The separation of cells

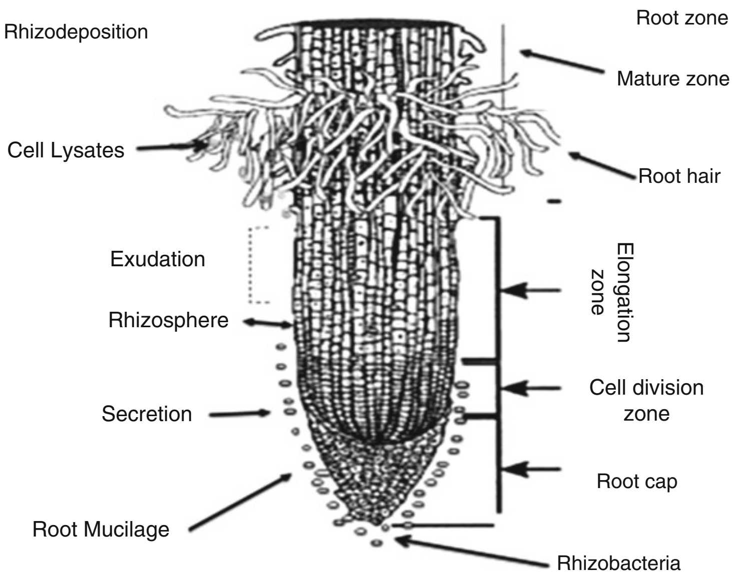

Fig. 6.3 Mechanisms of release of rhizodeposition that provide nutrients for plant growth-promoting rhizobacteria (PGPR) root colonization and growth based on classes of compounds, secretions and their functions in the rhizosphere

from the periphery of the cap can easily be observed under a microscope for numerous plant species. In field-grown maize, the detached cells were found alive at some distance from the root tip (Vermeer and McCully 1982), which indicates that border cells are still viable several days after their separation from the root. Among plants belonging to ten families, the viability of border cells after they separate from the root was demonstrated to be 90% or higher in most cases, except in the *Compositae* sunflower and *Zinnia,* for which most of the border cells were dead when they detached from the cap (Hawes 1990). Furthermore, in pea, detached cap cells exhibit different gene expression from that of attached cap cells (Brigham et al. 1995; Driouich et al. 2013). It is suggested that they play a significant role in engineering the rhizosphere ecology (Hawes et al. 1998; Fustec et al. 2010) and therefore, the term border cells were proposed instead of the original denomination "slough-off cap cells" (Hawes 1990; Samad et al. 2019). The suggested functions of root border cells are numerous: decrease in frictional resistance experienced by root tips (Bengough and McKenzie 1997; Sasse et al. 2018), regulation of microbial populations in the rhizosphere by attracting pathogens and preventing them from damaging the root meristem and by promoting growth gene expression in symbiotic microorganisms (Zhao et al. 2000) and protection against heavy metal toxicity such as aluminium (Morel et al. 1986; Huskey 2020).

6.2.3.2 Secretion of Mucilage by Roots

A mucilaginous layer has been frequently observed on the root surface of many plants (Table 6.3) (Oades 1978; Maeda et al. 2019; Hassan et al. 2019) and more particularly at the root tip, where it can form a droplet in the presence of water (Samsevitch 1965). There is no clear evidence that the epidermis and the root hairs secrete mucilage (Peterson and Farquhar 1996). In Sorghum, Werker and Kislev (1978) reported small drops of mucilage secreted by root hairs in addition to a fibrillar mucilaginous layer secreted by the epidermal cells. However, the mucilaginous layer observed on these parts of roots may derive from the mucilage secreted by the root cap (Vermeer and McCully 1982), from the degradation of epidermal cell walls (Foster 1982) or may be synthesized by rhizosphere microorganisms (Rovira et al. 1979). However, for most of the plants examined, the mucilage is secreted by the outer layers of the cap cells (Paull and Jones 1975) and it can be seen at the root tip of several plants (Miki et al. 1980).

The mucilage is composed of polymerized sugars and of up to 6% proteins (Bacic et al. 1987). The major sugars identified are arabinose, galactose, fructose, glucose and xylose (Knee et al. 2001; Feng et al. 2020). In ma 0A0; a molecular w 0A0;0A0;× 10 t> daltons, a density of 1.63 gcm^{-3} (Paull et al. 1975), a C content of 39% and a C:N ratio of 64 (Mary et al. 1993). The formation of the rhizosheath from root cap mucilage suggests that its mineralization by microorganisms is reduced or very slow. In vitro, root mucilage can readily be utilized by rhizosphere bacteria as a sole source of carbon (Knee et al. 2001; Galloway et al. 2020). Furthermore, in a laboratory experiment, Mary et al. (1993) demonstrated that maize muc s mineralized at 45% of the added C within 2 weeks. However, in the rhizosphere, mucilage mineralization may be delayed by the preferential use by

Table 6.3 Production of root cap cells and mucilage by roots of different plant species

Plant	Nature of carbon	Amount	Units	Comments
Zea mays	Root cap cells	1.52	μg C day^{-1} $root^{-1}$	Seedling grown in sand: Resistance to penetration =0.3 MPa. For calculations, the root cap cell is considered as a cylinder with a length of 80μm and a diameter of 21μm, a density of 1 g/cm^3 and a dry matter/fresh matter ratio of 0.072
Zea mays	Root cap cells	2.56	μg C day^{-1} $root^{-1}$	Same conditions as above except the resistance to penetration = 5.2 MPa
Zea mays	Root cap cells	2.8	μg C day^{-1} $root^{-1}$	Calculated assuming a C content of root cap cells of 40%
Pinus gossypium	Root cap cells	10,000	Cells day^{-1}	
Vicia faba	Root cap cells	420–636	Cells day^{-1}	
Zea mays	Mucilage	34	μg DM mg DM root $growth^{-1}$	
Zea mays	Mucilage	11–17	μg DM mg DM root $growth^{-1}$	Growth in axenic nutrient solution for 28 days
Triticum aestivum	Mucilage	29–47	μg DM mg DM root $growth^{-1}$	Growth in axenic nutrient solution for 25 days
Triticum aestivum	Root cap cells+ mucilage	3.2–6.4	μg DM mg DM root $growth^{-1}$	
Zea mays	Root cap cells+ mucilage	1250	m^3 ha^{-1}	Calculated from the size of the droplet at the root tip
Arachis hypogea	Root cap Cells+ mucilage	0.15	% of root C	Growth in axenic nutrient solution for 2 weeks

microorganisms of root exudates, which are more readily available and by the protection of mucilage due to its adsorption on the soil matrix (Sollins et al. 1996; Tian et al. 2020a, b).

6.2.3.3 Root Exudation

Excretion of organic compounds from roots was first reported as early as the end of the nineteenth century. In 1894, Dyer demonstrated the release of acidic substances from roots of barley, wheat and others (Table 6.4) (Krasil'nikov 1961; Tian et al. 2020a, b). The biochemical nature of compounds excreted by roots demonstrates a wide variety: simple and complex sugars, amino acids, organic acids, phenolics,

Table 6.4 Quantities of C in root exudates of different plant species

Plant	Amount	Units	Compounds	Comments
Hordeum vulgare	76–157	μgC plant day^{-1}	Exudates	Depending on mechanical constraint, 21 days of growth
Brassica napus	16–21	μgC plant day^{-1}	Total C	Sterile and non-sterile roots, calculated from original data
Acer saccharum	2.7–6.7	% root DM day^{-1}	Exudates	Defoliated-control
Agropyron smithii	0.01	% root DM day^{-1}	Reducing sugars	Defoliated/control, effect of temperature
Zea mays	0.03–0.06	% root DM day^{-1}	Sugars	Sterile and non-sterile roots, 23 days of growth
Zea mays	0.03–0.04	% root DM day^{-1}	Organic acids	Sterile and non-sterile roots, 23 days of growth
Zea mays	0.001	% root DM day^{-1}	Amino acids	Sterile and non-sterile roots, 23 days of growth
Triticum aestivum	121–153	μg C cm root $growth^{-1}$	Exudates	Sterile, nutrient solution: 2 or 4 day replacement
Triticum aestivum	196–226	μg C cm root $growth^{-1}$	Exudates	Sterile, non-sterile nutrient solution: 2-day replacement
Triticum aestivum	576–1174	μg C cm root $growth^{-1}$	Exudates	Nutrient solution: 2-day replacement, sterile-inoculated with pseudomonas putida
Zea mays	0.1–1.2	% root DM day^{-1}	Exudates	Calculated from original data, sterile, no or daily changes of nutrient solution, 10-day culture

alcohols, polypeptides and proteins, hormones and enzymes (Neumann and Romheld 2000; Meier et al. 2020). In the literature, the meaning of the term "exudation" may differ significantly. Exudates were defined as low molecular weight compounds diffusing passively from intact cells to the soil solution (Rovira et al. 1979; Liu et al. 2015). However, "root exudates" are often used to describe more generally the low molecular compounds released from roots regardless of the process by which they are deposited into the rhizosphere. The main low molecular weight compounds released passively from roots are sugars, amino acids and organic acids. They diffuse passively from the cytoplasm that is commonly three orders of magnitude more concentrated than the soil solution (mM vs. μM, respectively) (Neumann and Romheld 2000; Tsuno et al. 2018). For example, in maize roots, average concentrations are 86 mM for sugars (Jones and Darrah 1996), 9.5 mM for amino acids (Jones and Darrah 1994) and 10–20 mM for organic acids (Jones 1998; Meier et al. 2020). The lipid bilayer of the plasmalemma is a barrier to free diffusion of solutes because its permeability is reduced, especially for charged compounds compared with neutral molecules. However, the protons excreted by the H^+-ATPase provide an electrochemical gradient for the diffusion of anions (Jones 1998). Transient defects in the plasmalemma can also significantly increase its permeability, as suggested for amino acids (Chakrabarti and Deamer 1992).

6.2.3.4 Senescence of Root Epidermis

Behind the root tip, epidermal cells differentiate either into hair cells (trichoblast) or non-hair cells (atrichoblast). Root hairs are involved in anchorage, in water and nutrient uptake and in symbiosis (Kafkafi et al. 2002; Tian et al. 2020a, b). In recent years, extensive research has detailed the genetic control of root hair development, especially in *Arabidopsis*. From a study carried out by Dittmer (Dittmer 1949) on 37 species belonging to 20 angiosperm families, the size of root hairs is quite constant within a given species but is very variable between species. Root hairs are typically 80–1500μm long and have a diameter of 5–20μm. The root hair zone is on average 1 to 4 cm long (Kafkafi et al. 2002). The literature gives evidence that root hair density is also very variable between plants: 1 to 180 hairs mm^{-1} of root, 70 to 10,800 hairs cm^{-2} of root. Furthermore, environment strongly influences root hair development. For example, low levels of minerals, especially P and nitrate (Jung 2001), mechanical constraint, low O_2 partial pressure or high temperatures stimulate root hair formation. Similar effects can be observed when roots are exposed to ethylene, which suggests that ethylene could be involved in the regulation of root hair development by environmental factors (Michael 2001). There is little information about the lifespan of root hairs. Based on the loss of the nucleus, it was estimated that the longevity of root hairs was 2–3 weeks in wheat, barley and maize (Holden 1975). However, microscopic examinations indicate some cytoplasm lyses in 4-day-old hairs in maize. Thus, despite the fact that the cell wall can persist for several weeks or months (Kafkafi et al. 2002), the lifespan of root hairs is probably shorter, i.e., 2–3 days. If root hairs are considered as cylinders that have a dry weight: fresh weight (DW:FW) ratio of 0.072, a density equal to 1 g cm^{-3} and a C content of 40% DW, the calculation of the hair density of a 50 hairs mm^{-1} root indicates that small hairs (80μm in length, 5μm in diameter) correspond to 2.2 ng C mm^{-1}root, whereas large hairs (1500μm in length, 20μm in diameter) are equivalent to 680 ng C mm^{-1}root. Medium-size hairs (500μm in length, 10μm in diameter) correspond to 56 ng C mm^{-1}root. Theoretically, these amounts of C should be deposited into the soil after the hair death. However, to our knowledge, it is unknown if the cytoplasm material is released into the soil or recycled within the root tissue.

6.3 Techniques: A Pathway for Quantification

All of the organic carbon (C) found in the soil are primarily plant derived. Basing on the life cycle of plants, two main sources of C input in the soil can be distinguished:

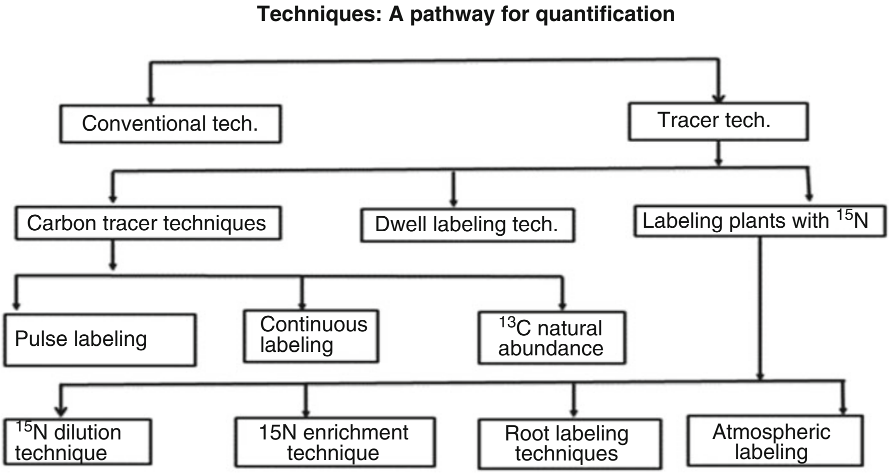

Fig. 6.4 Flow chart of different types of rhizodeposition quantification techniques

- Root and shoot remains contributing to the accumulation of soil organic matter (SOM) due to humification after plant death.
- Root exudates and other root-borne organic substances released into the rhizosphere during the plant growth, as well as root hairs and fine roots sloughed by root elongation.

The second source of C input into the soil means the amount of rhizodeposits has not been sufficiently investigated. The main problem is that profound results observed in plant physiology of root exudations can only partially be used under real soil conditions. The interactions of the roots with the mineral soil matrix and the soil microorganisms lead to the different C allocation and sequestration by roots when compared with the nutrient solution culture (Meharg and Killham 1991; Stevenel et al. 2019) or sterile soil (Merbach et al. 1991). Unfortunately, the wide spectrum of methods developed in plant physiology for investigations of root derived organic substances in nutrient solutions and artificial substrates cannot be directly applied to native soils. Consequently, our knowledge on the C input by roots into the soil is still incomplete. There are four main reasons causing this deficiency:

- Low concentration of root derived organic substances in the soil in comparison to the content of other organic substances.
- Fast decomposition ($T_{1/2} = 0.5$–10 days) by soil microorganisms of all organic substances released from roots.
- Appearance of the rhizodeposits in a narrow zone of soil adhering to the root surface.
- Difficulties in distinguishing between organic substances derived by SOM decomposition and microbial turnover and those released by roots (Fig. 6.4).

6.3.1 Carbon Tracer Techniques

Currently, three tracer methods are commonly used for the estimation of C input into the soil by plants: (1) pulse labeling, (2) continuous labeling and (3) C^{13} natural abundance. The first two methods are based on the artificial labeling of plants. Shoots are exposed to CO_2 in an atmosphere labeled with C^{14}, C^{13} or C^{11}. The shoots assimilate the label and translocate a part of it into soil. This C is incorporated into the root tissue, exuded as high and low molecular organic substances, sloughed as cell tissue by root elongation, and released as CO_2 derived from root respiration. Hence, the entire labeled C later found in all soil pools or evolved as CO_2 from the soil is plant derived. This allows the calculation of C input by plants into the soil on the background of soil organic C, which remains unlabeled.

6.3.1.1 Pulse Labeling

In the case of the pulse labeling, the shoots assimilate the labeled CO_2 for only a short period, and only once during the whole plant growth. In contrast to this, in the case of continuous labeling, the plants assimilate labeled CO_2 over a long period, mostly between the emergence of the first leaf and the sampling time. Different experimental systems for pulse and continuous labeling of plants are described in many publications (Sinyakina and Kuzyakov 2002; Stewart and Metherell 2000; Xiao et al. 2019; Zang et al. 2020). Although both methods only differ in the duration of the exposure period to the labeled CO_2, they are used for different aims. Pulse labeling, compared with continuous labeling, has the advantage of being easier to handle (Whipps 1990), provides more information on the recent photosynthate distribution at specific developmental stages of plants (Swinnen et al. 1994), and can be used for kinetic investigations of $^{14}CO_2$ evolution from the soil (Kuzyakov et al. 2001; Stevenel et al. 2019). The results obtained by pulse labeling correspond to the relative distribution of assimilated C at the moment of labeling and does not reflect the distribution of total unlabeled C in different plant parts, but correspond rather to the product of total C in the plant part multiplied by its growth rate at the moment of labeling. The total amount of C assimilated by the plant is unknown and can be calculated only roughly. As partitioning patterns change during plant growth, the C^{14} distribution at one stage of development cannot be applied to another or to a whole growth period. The most important limitation of the pulse labeling is that the results of C allocation observed for a specific growth stage cannot be directly transferred for the whole growth period. However, a series of labeling pulses applied at regular intervals during plant growth have been found to provide a reasonable estimate of the cumulative belowground C input (Warembourg and Esterlich 2000).

6.3.1.2 Continuous Labeling

In the case of continuous labeling, the total amount of assimilated C is known. In addition, the distribution of labeled C corresponds to the distribution of total C, as long as it was applied from first leaf emergence to harvest time (the specific ^{14}C activity or ^{13}C abundance is equal in all plant parts). Therefore, continuous labeling is particularly appropriate for the estimation of the amount of total C transferred by the plants into the soil and belowground pools during the labeling period (Meharg 1994; Stevenel et al. 2019). Continuous labeling is also useful for the separation of root-derived and SOM-derived CO_2 (Whipps 1987; Zhou et al. 2020). Continuous labeling requires special equipment for exposing the plants over a long period to $^{14}CO_2$ with constant ^{14}C specific activity or $^{13}CO_2$ with ^{13}C enrichment. In addition, the air temperature and moisture conditions must be controlled inside the labeling chamber. For both pulse and continuous labeling methods, special airtight equipment is necessary to separate the soil air and the atmosphere. From the different C isotopes, the radioactive ^{14}C has been used in most studies with pulse and continuous labeling so far. This preferential use of ^{14}C is based on the high sensitivity, the lower costs for purchase and analyses, and easier sampl h ^{13}C or ^{11}C. Since ^{11}C has a short half-life (20.4 min), only ^{14}C and ^{13}C are appropriate for continuous labeling. An important advantage of the described tracer techniques compared with traditional methods is that the amount of tracer which entered the system is exactly known. After the partitioning of assimilates, it is possible to calculate the balance of the C in the atmosphere–plant–soil system, as well as to estimate the system losses. Traditional methods are less accurate and can be used only to calculate the distribution of C between the measured C pools. Meharg (1994) published a more detailed review on the features and applications of pulse and continuous labeling.

6.3.1.3 ^{13}C Natural Abundance

The third method, ^{13}C natural abundance, is based on the discrimination of ^{13}C and ^{12}C isotopes during CO_2 assimilation by plants with different photosynthesis types. Enzyme Rubisco in C3 plants leads to a ^{13}C depletion of about -27% ($-35\% \leq \delta C^{13} \leq -20\%$) when compared with atmospheric CO_2. Phosphoenol pyruvate carboxylase (C4 plants) results in a depletion of about -13% ($-15\% \leq \delta C^{13} \leq -7\%$). The δC^{13} values (Table 6.5) of different plants are reviewed by Farquhar et al. (1989), Boutton et al. (1998) and Stevenel et al. (2019).

The effects of humification and other microbial-related processes on δC^{13} are thought to be negligible. Therefore, the soils developed under C3 or C4 vegetation contain SOM with $\delta C^{13} = -27\%$ or -13%, respectively (Cheng 1996). The method is based on cultivation of C3 plant on a C4 soil, or vice versa, and the estimation of rhizodeposition according to the δC^{13} value in soil C pools or CO_2 evolved from soil. This method can be considered as a variation of the continuous labeling, because the plants and soil are permanently labeled. However, the labeling of

Table 6.5 Quantification of rhizodeposits in plants by using 13C technique

Plants	Amount
Hordeum vulgare	76–157μg plant^{-1} day^{-1}
Brassica napus	16–21μg plant^{-1} day^{-1}
Acer saccharum	2.7–6.7% root DM day^{-1}
Agropyron smithii	0.01% root DM day^{-1}
Triticum aestivum	121–153μg cm^{-1} root growth
Zea mays	0.1–1.2% root DM day^{-1}

plant and soil occur naturally, not artificially, as is the case of pulse or continuous labeling methods described above. This method can easily be used under field conditions (Rochette and Flanagan 1997; Stevenel et al. 2019) because special equipment for plant labeling and separation from the atmosphere is not necessary. The last feature and the future development of mass-spectrometry will promote the use of this method in forthcoming investigations.

The limitations of the ^{13}C natural abundance method are caused by soil–plant pairs. Situations where C3 plants grow on a C4 soil, or vice versa, are unnatural. Hence, the application of this method is restricted to places where soils developed under C3 vegetation allow the growth of C4 plants and vice versa. Additionally, the high resolution and high-sensitive mass-spectrometry are necessary for C^{13} analyses because a maximal range of only 14% is available for all variations of the C^{13}/C^{12} ratio. At the same time, the variability of $\delta^{13}C$ value in soil or plant is about +1–2% (Cheng 1996; Xiao et al. 2019). For the last two reasons mentioned only a rough estimation of rhizodeposition in the soil and in the pools with high C exchange rates with the root-derived C (e.g., microbial biomass, dissolved organic C, active pools of SOM, etc.) is possible.

6.3.2 Labeling Plants with ^{15}N

Rhizodeposition of N has been estimated using different approaches. Either plants are previously labeled and transplanted (Rroço and Mengel 2000), or plants are labeled with N^{15} via roots, by labeling the shoot and/or leaves selectively with liquid N^{15} or with gaseous N^{15}. In recent years there have been various attempts to compare different N^{15} labeling techniques (Yasmin et al. 2006; Stevenel et al. 2019). Here, we describe the various labeling techniques and their advantages and disadvantages in estimating N rhizodeposition.

6.3.2.1 ^{15}N Dilution Technique

The label is provided directly to the soil and N fixation is estimated by the input of N^{14} from the atmosphere. This method is reliable for measurement of N2 fixation by legumes and transfer to companion plants (Table 6.6) (Paynel et al. 2008, He et al. 2020) but is strongly influenced by small differences in the spatial and temporal distribution of soil N^{15} when used for measurement of N rhizodeposition (Khan et al. 2007; Smith and Chalk 2020). Poth et al. (1986) used a soil with very low nitrogen content and labeled this soil with $^{15}NH_4$ for six years to increase the accuracy of the measurement of rhizodeposition by pigeonpea plants in a greenhouse study.

6.3.2.2 $^{15}N_2$ Enrichment Technique

By this technique, nodulated roots are exposed to $^{15}N_2$, which is a direct way to measure the input of fixed N2 into the rhizosphere (Russelle et al. 1994; Stevenel et al. 2019). However, this technique requires specific equipment and cannot be applied

Table 6.6 Quantification of rhizodeposits in plants by using 15 N technique

Plants	% of total plant-N		NdfR in % of BGP-N
	BGP-N	NdfR	
Peas	15	12.8	82
Faba bean	14	13.4	78
White lupin	17	15.8	85
Blue lupin	28	18.5	65
Chickpea	53	44	88
Mung bean	20	17	85
Pigeon pea	47	37	78
Grass pea	18	9.2	50

easily in the field. Furthermore, free-living N_2-fixing bacteria can use ^{15}N and complicate interpretation of results.

6.3.2.3 Shoot Labeling Techniques

Several shoot labeling techniques have been used to apply N^{15} that do not follow the natural pathway of N-assimilation. Plants are labeled with a single pulse or multiple pulses either by stem, petiole, leaf or leaf-flap feeding. Commonly, N^{15} is applied as highly enriched ^{15}N-urea, $^{15}NH_4^+$ or $^{15}NO_3^-$.

Leaf feeding is done by leaf spraying or by leaf, leaf-flap and leaf-tip immersion. For the latter, leaves are either remaining intact (Høgh-Jensen and Schjørring 2001), cut at the tip, or cut in half (Yasmin et al. 2006) and are immersed in a solution containing ^{15}N-urea (Yasmin et al. 2006), $^{15}NO_3^-$ or $^{15}NH_4^+$ solution (Hertenberger and Wanek 2004). Leaf pulse labeling of plants resulted in a similar ^{15}N enrichment of the stem as with a continuous split-root technique, but ^{15}N enrichment in the roots was much lower in the leaf labeling (Jensen 1996). Application of a ^{15}N-solution using leaf feeding holds the potential risk of soil contamination by run-off from foliage (Khan et al. 2002) even though precautions can be applied (Zebarth et al. 1991).

The same holds true for petiole feeding, where the highly enriched petioles might be detached and contaminating the soil (Khan et al. 2002). One solution to this probl 0A0;n a vial uperscript>N-solution (McNeill et al. 1997). The tip of a single leaf, which was cut under water, was placed into a 2 ml vial containing 1 ml of a 0.25% ^{15}N-labeled (99.6 atom%) urea solution and sealed to prevent solution loss by evaporation (McNeill et al. 1997). Plants took up less solution (deionized water) when instead of leaves petioles were used, and solution uptake varied depending on position of the leaf and the environmental conditions, which are influencing the transpiration stream of plants (McNeill et al. 1997). When comparing leaf-flap feeding and petiole feeding, leaf-flap feeding resulted in more consistent levels of root enrichment in mung bean and in higher enrichment for roots of pigeon pea (Khan et al. 2002).

One of the stem feeding techniques used for shoot labeling plants with ^{15}N is the wick method first published by (Russell and Fillery 1996). The wick method was developed for labeling plant material and BGP of woody legumes with ^{15}N in situ.

The wick method might also provide a tool for double labeling plants with ^{13}C and ^{15}N in situ, by applying a highly enriched solution with a defined amount of ^{13}C and ^{15}N into the plant. In situ methods hold the advantage that the characteristic spatial distribution of roots and root-derived material remains intact (Zebarth et al. 1991; Shao et al. 2020) and that the contact between soil and root material with the associated faster turnover is provided. For the wick method a hole is drilled through the stem of the plant. Then a cotton wick is passed through the hole and covered with a silicone tube. The ends of the wick are passed into a vial containing the labeling solution (e.g., ^{15}N-urea). All connections where solution loss can occur are sealed with plasticine to prevent solution loss by transpiration.

6.3.2.4 Root Labeling Techniques

The split-root technique was used in a series of experiments (Schmidtke 2005). For this method, roots are equally split between a compartment with vermiculite or soil containing the ^{15}N-tracer (e.g., $^{15}NO_3^-$, $^{15}NH_4^+$) and a soil compartment to measure the NdfR (Jensen 1996). The split-root technique allows a continuous ^{15}N labeling of various plant species (Sawatsky and Soper 1991), providing a tool for a continuous labeling of plants using the natural pathway of N assimilation. This guarantees the incorporation of the ^{15}N label in all N pools of the plant (Jensen 1996). The method can also be used to estimate the N transfer of rhizodeposit-N into associated plants (e.g., from legumes to grasses) (Jensen 1996). However, the ^{15}N fertilizer is often a significant proportion of total plant N (Merbach et al. 2000) and therefore influences rhizodeposition patterns. The application of nutrients containing the tracer altered plant development in comparison to an undisturbed control (Jensen 1996). Furthermore, the root system is substantially disturbed by the method (Khan et al. 2002), and quantitative estimation of the NdfR accounts only for a part of the root system (Rroço and Mengel 2000) making a complete ^{15}N-balance difficult (Merbach et al. 2000). The method is not suitable for in situ and field investigations and cannot be used for plants with tap roots without substantially influencing the rooting system of the plant.

6.3.2.5 Atmospheric Labeling

The technique of atmospheric labeling is technically more demanding than shoot labeling (Khan et al. 2002). It requires expensive enclosure equipment which limits application in the field (McNeill et al. 1997). Using this method, legumes can be labeled by applying $^{15}N_2$ which is assimilated symbiotically (Warembourg et al. 1982). Such an approach runs at risk of non-symbiotic $^{15}N_2$-fixation influencing the estimates of legume derived BGP-N (McNeill et al. 1997). Plant shoots and leaves can also be labeled by leaf assimilation of $^{15}NH_3$ when plants are exposed to gaseous NH_3 in the atmosphere (Merbach et al. 1999). The $^{15}NH_3$ is released from $(^{15}NH_4)_2SO_4$ after placement into NaOH (Merbach et al. 1999). Labeling can be done using multiple pulses (Janzen and Bruinsma 1989) or a continuous labeling. Short pulses have the advantage that plants are exposed to NH_3 only for a short period of time, making regulation of the atmospheric composition unnecessary (Janzen and Bruinsma 1989). Atmospheric labeling with $^{15}NH_3$ requires separation of soil and plant by sealing the soil surface during exposure to gas. A further disadvantage is that quantification of the uptake is difficult, particularly under field conditions. Moreover, the N application does not follow the physiological pathway of N assimilation. After NH_3exposure, an increased total N uptake but no total dry matter increase was observed, and an increase of shoot yield relative to root yield (dry matter and N) was documented with increasing frequency of NH_3application (Janzen and Bruinsma 1989).

6.3.2.6 Cotton-Wick Technique

The *cotton-wick technique* was proposed by Russell and Fillery (1996). ^{15}N labeling solution is provided to the plant by means of a cotton-wick passing through a hole in the plant stem. These authors have shown that the transfer of solutions into young lupin plants is more effective using the cotton-wick method than the leaf feeding method. N uptake by the cotton-wick technique is mainly driven by the transpiration stream, avoiding active mechanisms occurring with root or leaf immersion. Results reported by Russell and Fillery (1996), McNeill and Fillery (2008) and Stevenel et al. (2019) confirm that this method seems accurate for assessing belowground N of field-grown lupin and provides a more homogeneous ^{15}N distribution in the plants compared with leaf feeding techniques (Mayer et al. 2003). It has also been confirmed for faba bean, chickpea, mung bean, pigeon pea, pea, white lupin, soya bean and oat (Mahieu et al. 2007; Zang et al. 2018). Fortnightly pulses of high ^{15}N-urea (99% atom^{15}N) were found to be more efficient than a weekly application (Russell and Fillery 1996) and provide similar results to pulses applied at given growing stages (six leaf stage, flowering and pod filling; Mahieu et al. 2007). In Mayer et al. (2003) the amount of urea applied to pea plants at each pulse was calculated from dilution curves, to keep an average ^{15}N content of 2.5% atom ^{15}N excess of the plant N during the growing demand. All experiments undertaken on pea showed that ^{15}N recovery was around 90% (84–94%) in the greenhouse and 50–76% in the field (Wichern et al. 2007). Furthermore, the longer the experiment, the lower ^{15}N recovery in the plant-soil system (Mahieu et al. 2007). In cotton-wick, as in leaf-flap and petiole feeding, above ground parts are markedly more ^{15}N enriched than roots. Root enrichment ranged between 1.1 and 1.4% atom^{15}N excess in Wichern et al. (2007) but reached up to 3.6% atom ^{15}N excess in Mahieu et al. (2007). However, cotton-wick cannot be used with thin-stemmed species such as chickpea (Yasmin et al. 2006). Few attempts have been made to inject ^{15}N-urea directly into the stem with a syringe. Chalk et al. (2002) did not obtain reliable results with *S. rostrata*, probably because of its hollow stem (Table 6.7).

6.4 Interaction: Plant–Rhizodeposits–Soil

There are many factors that influence rhizosphere activity; among them most important ones are (i) microbial activity, (ii) soil processes, (iii) soli solution pH, (iv) soil organic matter and (v) plant root exudation (Fig. 6.5). These five factors interact simultaneously in rhizosphere and modify the rhizosphere environment to

Table 6.7 Methods for plants labeling with radio isotopes and their advantages and disadvantages

Labeling method	Technique	Subtype	Advantages	Disadvantages
Shoot Labeling	Leaf feeding	Leaf-tip immersion leaf spraying leaf-flap feeding	Undisturbed root system; in situ conditions; fast solution uptake; can be used under field conditions; labeling of most plants possible; can be used for investigating rhizodeposition at different growth stages and the whole growth phase of plants when applying multiple pulses	Lower enrichment of roots in comparison with the split-root technique; preferential enrichment of leaves; balance difficult as losses might occur; high urea concentrations cause leaf damage; soil contamination by runoff from leaves; solution uptake and root enrichment varies depending on the position of the leaf labeled
	Petiole feeding		Undisturbed root system; in situ conditions; fast solution uptake; can be used under field conditions; labeling of most plants possible	Contamination of soil by detached petioles; lower uptake in comparison with leaf feeding
	Stem feeding	Wick method	Undisturbed root system; in situ conditions; can be used under field conditions; applied amount known which makes balance possible; can be used for investigating rhizodeposition at different growth stages and the whole growth phase of plants	Enrichment depends on solution uptake; uptake mechanisms not known; no clear pulse or continuous labeling approach; only plants with stems can be labeled; cereals can be labeled only after appearance of the first knot
	Stem injection		Easy and fast method; plant growth stages can be investigated at small intervals; precise pulse labeling	Only small amounts can be applied; difficult to use for tracing plant-derived 15N into the soil because of low root enrichment
Atmospheric labeling	$^{15}N_2$		Give most accurate estimate of N2-fixation; undisturbed root system; in situ conditions	Can only be used for legumes

(continued)

Table 6.7 (continued)

Labeling method	Technique	Subtype	Advantages	Disadvantages
	$^{15}NH_3$		Undisturbed root system; in situ conditions; can be used for estimating rhizodeposition at different growth stages and during the whole growth phase	High concentra onditions Difficult
Root labeling	Pre-cultivation of plants in 15 N-solution		Natural N-uptake pathway; homogeneous labeling during pre-cultivation; high enrichment; can be used for estimating rhizodeposition at different growth stages	No in situ conditions possible; investigation of later growth stages only; continuous in situ labeling impossible
	Split-root technique		Natural N-uptake pathway; continuous labeling; high enrichment; early growth stages can be labeled; homogeneous labeling; can be used for estimating rhizodeposition at different growth stages and during the whole growth phase; only continuous labeling technique	Only one part of the root system is investigated; cannot be used for plants with tap-roots; strong disturbance of the root system; no field and complete in situ conditions; application of tracer can be a significant N-input; no complete balance; over estimation of N rhizodeposition

facilitate plant for nutrient mobilization and acquisition (Crowley and Rengel 1999; Rakshit and Bhadoria 2007) Benizri and Kidd 2018). Their role in nutrient mobilization is given by the (modified from Zhang et al. 2002). Nutrients in soil remain in three main pools: (a) organic pool, (b) inorganic pool and (c) colloid. Soil solution nutrients remain in equilibrium with those pools via the process of mineralization–immobilization, dissolution–precipitation, and fixation–release from the pools. These processes are influenced by rhizosphere element like microbial activity, enzyme activity, root exudates and rhizosphere pH. The nutrients in solution are uptaken by plant roots and transported through xylem and help in food synthesis. The synthesized foods are translocated downward through phloem and in the meantime undergo transformation to several root exudates and released in rhizosphere. These root exudates again influence the soil processes that affect nutrient equilibrium in soil solution.

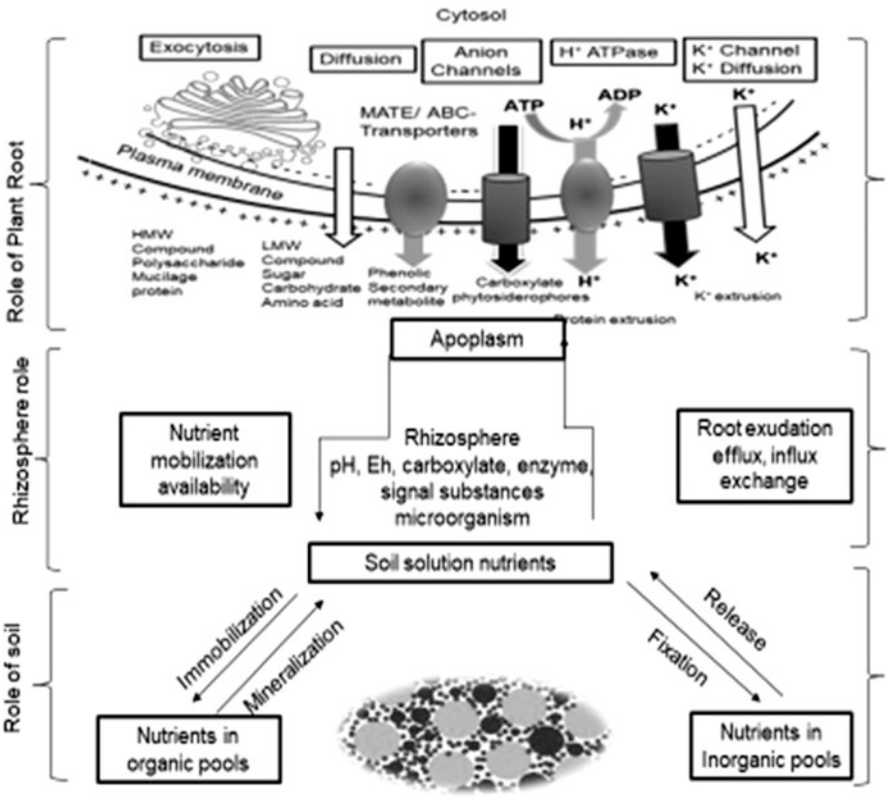

Fig. 6.5 Nutrient interactions in the plant–rhizosphere–soil continuum and nutrient flow from soils to plants via rhizosphere processes as a linkage between plant processes and soil processes

Root exudates that influence the nutrient equilibrium in soil solution have definite mechanism to be released. They are: (a) diffusion, (b) anion channel and (c) vesicle transport.

6.4.1 Diffusion

In this release mode, low molecular weight organic compounds such as sugars, amino acids, carboxylic acids and phenolic are released in response to concentration gradients between the cytoplasm of intact root cells (millimolar range) and the soil (micromolar range) (Bertin et al. 2003; Neumann and Römheld 2012). Membrane permeability, which depends on the polarity of the molecules to be released, determines if direct diffusion through the lipid bilayer of the plasma lemma is possible. Lipophilic exudates mainly release through this method (Guern et al. 1987). Diffusion induced exudation of amino acids or malate from plant roots has been calculated at rate of approximately 0.3 nmol $hr.^{-1}$ cm^{-1} root length or 120 nmol $hr.^{-1}$ g^{-1} root fresh weight (Jones et al. 1994). Root exudation of amino acids and sugars occurs by passive diffusion, and is enhanced under stress by modification of the membrane integrity under nutrient deficiency (K,P and Zn), temperature extremes, or oxidative stress (Cakmak and Marschner 1988; Jones et al. 1994; Naureen et al. 2018).

6.4.2 Anion Channel

Root exudation (e.g., citrate, malate, oxalate), generally exuded in high concentrations through ion channel under specific stress condition such as nutritional deficiency or Al toxicity (Bertin et al. 2003; Neumann and Römheld 2012). Experimental studies using anion channel indicated the release of malate and citrate in wheat and maize under Al stress (Piñeros and Kochian 2001) and citrate exudation under P deficiency in *Lupinus albus* (Zhang et al. 2001). Further studies are needed to investigate physiology of the membrane to characterize the mechanism of transport specifically. In addition, the cloning of anion channel genes would also be helpful to further our understanding of root exudation mechanisms.

6.4.3 Vesicle Transport

Through vesicular transport high molecular weight compounds are released (Battey and Blackbourn 1993; Neumann and Römheld 2012). Golgi vesicles transport mucilage polysaccharides across the root cap while proteins such as (acid phosphatase, peroxidase) are transported from polysomes to endoplasmic reticulum through vectorial segregation (Neumann and Romheld 2000). Through vesicle high molecular weight substances like phenolics (Gagnon et al. 1992), phytosiderophores (Nishizawa and Mori 1987) released, but the exact mechanisms utilized remain unknown. Root exudate chemical composition is altered in rhizosphere through physical, chemical and biological processes in the soil like sorption, metal oxidation, microbial degradation (Huang et al. 1999). The biological activity of chemicals in the rhizosphere may be altered rapidly in terms of their efficacy because of chemical oxidation, microbial breakdown or immobilization by irreversible binding to soil particles. This alteration in activity can occur before the compound(s) in question reach a biological target (Cheng 1995).

6.5 Rhizodeposition: Impact in Nutrient Mobilization

6.5.1 Carbon Dynamics: Priming and Mineralization

The newly applied plant residue can either stimulate or retard decomposition rate of soil humus (Fig. 6.6). The change in decomposition rate is described as priming and is generally positive. Mechanisms of rhizosphere priming:

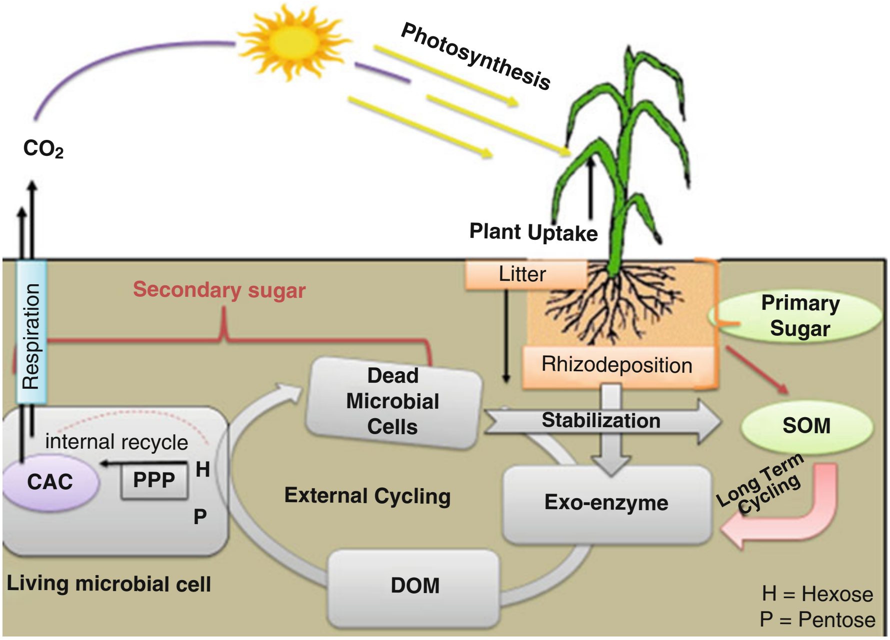

Fig. 6.6 Simplified diagram of the fates of rhizodeposited carbon (C) derived from living roots. Boxes correspond to C pools, while arrows correspond to processes and flows between C pools

- *Drying effect or drying and wetting hypothesis:* Drying and rewetting cycles enhance SOM decomposition in cultivated top soil than un-planted soil (Sala et al. 1992; Lu et al. 2019).
- *Aggregate destruction hypothesis:* Growing roots break down aggregates thereby causing exposure of SOM to microbial action and increase SOM decomposition (Reid and Goss 1982; Zhu et al. 2014).
- *Root uptake of soluble organic substances:* Microbial activity is reduced in rhizosphere when roots uptake released exudates in significant amount, C source is also reduced as a result SOM decomposition also decreases (Reid and Goss 1983; Zhu et al. 2014; Dotaniya and Meena 2015).
- *Enhancing microbial turnover rate due to faunal grazing:* Microorganism predation by fauna in rhizosphere increases mineralized N and CO_2 release (Alphei et al. 1996; Zang et al. 2018).
- *Competition for N mineralization between plant root and rhizosphere microorganism:* Plant root uptake N causing a deficiency of N for microbes in rhizosphere, thereby declining microbial growth and metabolism as well as soil organic matter decomposition (Bottner et al. 1999; Zang et al. 2018; Wang et al. 2020).

- *Preferred substrate utilization:* Root exudates and soil organic matter vary in availability to microbes. They first take up easily available root exudates followed by SOM. So SOM decomposition rate is low at the initial stages (Sparling et al. 1982).
- *Microbial activation:* By easily available substrates.

An increase in rhizodeposition enhances the population of r-strategist microorganisms, they have a high reproduction rate. For this they need C and energy that comes from oxidation of SOM releasing CO_2.

6.5.2 Nitrogen Dynamics

When nitrogen is applied in soil in ammonium form it has four fates: (a) plant uptake, (b) transformation to organic form, (c) fixation to clay and (d) nitrification where valence of N changes from −3 to +3 by activity of *Nitrosomonas* and then to +5 by the activity of *Nitrobacter* through formation of NO_2^- and NO_3^-, respectively, through the intermediate of hyponitrite (Fig. 6.7). Nitrate thus formed also have three fates: (a) plant uptake, (b) leaching and (c) denitrification to N_2 or N_2O by the activity of *Pseudomonas*, *Bacillus,* etc. N_2O is responsible for global warming and N_2 is fixed by *Rhizobium*.

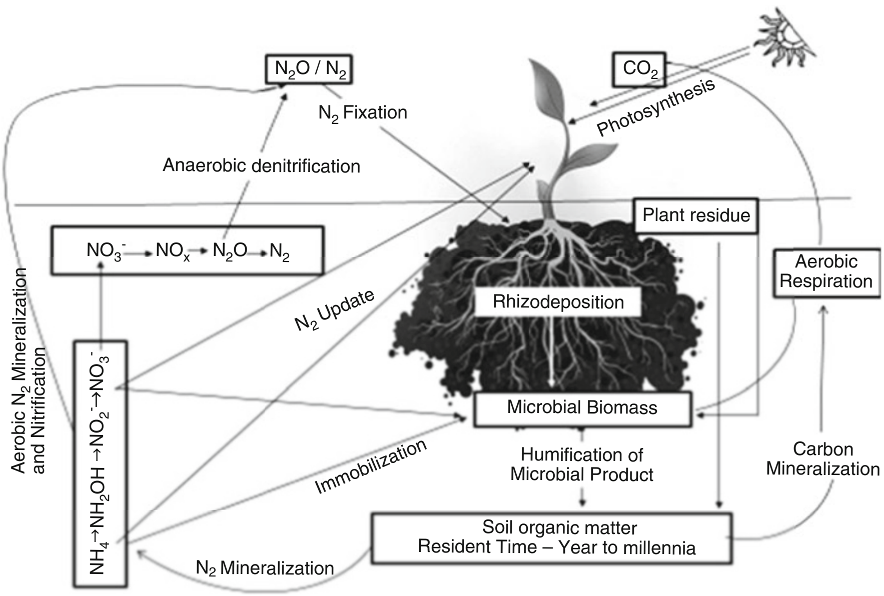

Fig. 6.7 Simplified diagram of Mechanisms of nitrogen dynamics in rhizodeposition

6.5.2.1 Biological Nitrogen Fixation

Biological nitrogen fixation can be represented by the following equation, in which two moles of ammonia are produced from one mole of nitrogen gas, at the expense of 16 moles of ATP and a supply of electrons and protons (hydrogen ions):

$$N_2 + 8H + +8e^- + 16\ ATP = 2NH_3 + H_2 + 16ADP + 16\ Pi$$

This reaction is performed exclusively by prokaryotes (the bacteria and related organisms), using an enzyme complex termed nitrogenase. This enzyme consists of two proteins—an iron protein and a molybdenum-iron protein, as shown below. The reactions occur while N_2 is bound to the nitrogenase enzyme complex. The Fe protein is first reduced by electrons donated by ferredoxin. Then the reduced Fe protein binds ATP and reduces the molybdenum-iron protein, which donates electrons to N_2, producing HN=NH. In two further cycles of this process (each requiring electrons donated by ferredoxin) HN=NH is reduced to $H_2N–NH_2$, and this in turn is reduced to $2NH_3$ (Postgate 2007; Zang et al. 2018; Archontoulis et al. 2020).

6.5.2.2 Role of Flavonoid in N Fixation

The host plants produce flavonoids in the rhizosphere which acts as a signaling molecule for Nod genes. These signals can be perceived by a specific bacterial receptor, NodD, which acts as a transcriptional activator of other nodulation genes. The nod gene products are involved in production of a nodulation signal, the Nod factor, which is a lipo-chito-oligosaccharide (Franche et al. 2009; Archontoulis et al. 2020), which causes curling of root hairs enveloping the bacterium. The flavonoid is host specific like *Phaseolus vulgaris* producing delphinidin (3,5,7,3′,4′,5-′-hexahydroxyflavylium) and kaempferol (3,5,7,4′-tetrahydroxyflavonol), *Glycine max* releases daidzein (7,4′-dihydroxyisoflavone) and genistein (5,7,4-′-trihydroxyisoflavone), whereas *Medicago sativa* exudates luteolin (5,7,3′4-′-tetrahydroxyflavone) and chrysoeriol (3′-methoxy-5,7,4′-trihydroxyflavone) (Pinton et al. 2007; Mo et al. 2019).

6.5.3 Phosphorus Dynamics

6.5.3.1 Inorganic P

Phosphorus solubilizing capacity of microbes is related to release of metabolites such as organic acids, which through their hydroxyl and carboxyl groups chelate the cation bound to phosphate, and soluble phosphorus released in soil (Fig. 6.8) (Sagoe et al. 1998; Hu et al. 2020). Inorganic P solubilization is carried out by PSB through the action of organic and inorganic acids, in which hydroxyl and carboxyl groups of acids chelate cations (Al, Fe and Ca) and decrease the pH of basic soils (Kpomblekou and Tabatabai 1994). Organic P mineralization is carried out by the action of several phosphatases (also called phosphohydrolases) (Rodríguez et al. 1999). Phosphorus, the second most important element, faces a problem of fixation

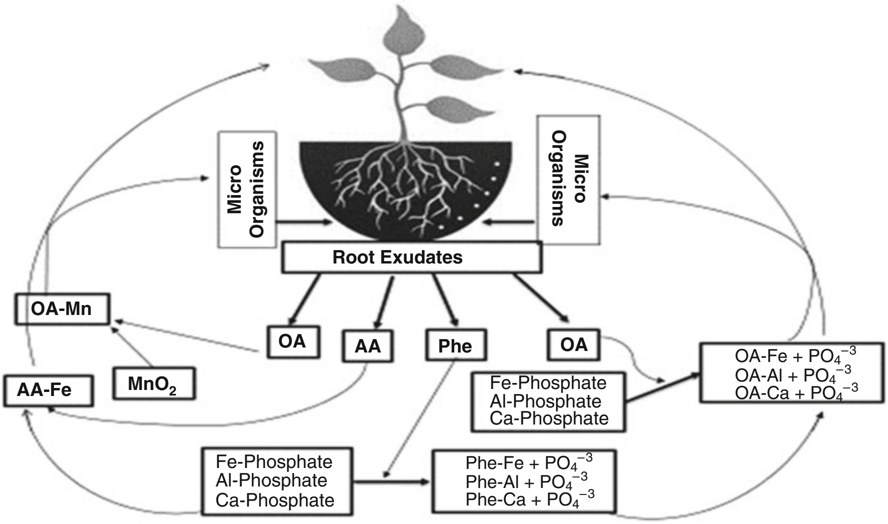

Fig. 6.8 Schematic diagram of soil phosphorus mobilization and immobilization by bacteria

and largely of precipitation. P is mobilized by microbes through by (a) chelation, (b) acid action and (c) release of CO_2.

- *Chelation:* We know from different study that phosphate solubilized by the combined effect of pH decrease and organic acids production (Fankem et al. 2006). PSB produces carboxylic acids which have high affinity to calcium, and is able to solubilize more phosphorus than acidification alone (Staunton and Leprince 1996). Organic anions and associated protons are also effective in solubilizing precipitated forms of soil P (e.g., Fe and Al - P in acid soils, Ca - P in alkaline soils) through chelation of metal ions and facilitate the release of adsorbed P through ligand exchange reactions (Jones 1998). Ryan et al. (2001) showed that phosphorus desorption potential of different carboxylic anions lowers with decrease in stability constants of Fe or Al–organic acid complexes (log K_{Al} or log K_{Fe}) in the order: citrate>oxalate>malonate/malate>tartrate> lactate>gluconate>acetate>formiate.
- *Acid action:* Oxidation of nitrogenous and inorganic S compounds produces inorganic acids like nitric acids and sulphuric acids, which react with rock phosphate and increase soluble P (Martins et al. 2011).
- *Microbial release of CO_2:* In calcareous soil P solubility is governed by CO_2 production by microbes. Lindsay (1979) established the equation $\log H_2PO_4 - \log Pco_2 = -9.23 + pH$, which implies that at any given pH increase in concentration of CO_2 will also increase the solubility of H_2PO_4 by decreasing the activity of Ca^{2+} in soil by formation of $CaCO_3$. Tang et al. (2014) showed that in the case of wheat, lentil, chickpea, intercrop wheat-chickpea, and intercrop wheat-lentil,

rhizospheric soil has the higher activity of microbes and subsequent releases more CO_2 than bulk soil.

6.5.3.2 Organic P

Organic matter decomposition in soil is carried out by numerous saprophytes, which influence the release of orthophosphate from the carbon structure of the molecule. The degradability of organic phosphorous compounds depends mainly on the physicochemical and biochemical properties of their molecules, e.g., nucleic acids, phospholipids and sugar phosphates are easily broken down, but phytic acid, polyphosphates and phosphonates are decomposed more slowly (Ohtake et al. 1996; McGrath et al. 1995). The dephosphorylating reactions involve the hydrolysis of phosphoester or phosphoanhydride bonds. The phosphohydrolases are two types in acidic or alkaline. The acid phosphohydrolases, unlike alkaline phosphatases, show optimal catalytic activity at acidic to neutral pH values. Release of acid phosphatase by plant roots or microbes or alkaline phosphatase (Tarafdar and Claassen 1988) enzymes hydrolyses the soil organic P or split P from organic residues.

6.5.3.3 P Acquisition by VAM

Under P deficiency plant roots release strigolactone that helps in sporulation and subsequent colonization of arbuscular mycorrhizal fungi (Basak et al. 2020; Parihar et al. 2019, 2020). Mycorrhizal plants can acquire inorganic P (Pi) either directly from the soil through plant specific phosphate transporters (PT), or by uptake and transport systems of the fungi. The AMF fungus in extra radical mycelium contains a high-affinity phosphate transporter (Benedetto et al. 2005; Rakshit and Bhadoria 2009) and that absorbs Pi in the vacuoles of extra radical hyphae in the form of poly P (Ezawa et al. 2003). Poly P chains are then transferred by means of a motile tubular vacuolar network (Uetake et al. 2002) in the intraradical compartment, then Pi ions are released through hydrolysis of poly P (Ezawa et al. 2002). Mycorrhiza specific PT has recently been characterized in potato, barley and *M.truncatula* (Harrison et al. 2002; Karandashov et al. 2004; Paszkowski et al. 2002), whereas PT genes were isolated from the AM fungi like *Glomus versiforme* (*GvPT*), *G. intraradices* (*GiPT*), and *G. mosseae* (*GmPT*).

6.5.4 Potassium Dynamics

Potassium in soil is present in four different pools—soil solution K, exchangeable K, fixed or non-exchangeable K and structural K in primary minerals. Soil potassium availability to plant roots is dependent on reversible transfer of K between the pools (Syers 2005; Badge and Adlakha 2019; AL-Hamandi 2020). A large number of soil microorganisms is involved in the solubilization of insoluble and fixed forms of K into available forms of K which is easily absorbed by plants (Li et al. 2006; Zarjani et al. 2013; Gundala et al. 2013; Verma et al. 2017).

Potassium ions are taken up from rhizosphere zone. It is reported that K uptake leads to K depletion (for water extractable, exchangeable and non-exchangeable K) in the rhizosphere (Claassen et al. 1986; Hinsinger 1998; Hinsinger et al. 2011). However, several authors have reported that nutrient availability is increased in the rhizosphere with special reference to K content and availability in the rhizosphere zone due to presence of higher amount of illite like layers in the rhizosphere compared to the bulk soil (Turpault et al. 2008). Bourbia et al. (2013) conducted a study in North Kabylia (Algeria) in 16 sites (14 Cambisol +2 Vertisol) in olive (*Olea europaea* L.) to understand the K status in bulk and rhizosphere soil. They found that the quantities of water extractable K, exchangeable K and slowly exchangeable K increased in rhizosphere soil than bulk soils of the 16 sites. They provided reasons for this increase:

- Mass flow of water helped to bring some K^+ in the vicinity of the roots just like Ca^{2+} in most soils (Barber 1995; AL-Hamandi 2020).
- Lower pH and the secretion of organic acids and ligands lead to faster weathering of primary minerals (Uroz et al. 2009). The intensified weathering can generate more K from primary minerals and contribute to its higher availability in the rhizosphere.
- Higher CEC and clay contents in the rhizospheric soil compared to the bulk soil explain the cause of higher exchangeable and slowly exchangeable K values in the rhizosphere.
- The higher K content in the rhizosphere can be explained by the fact that roots foraged for nutrient rich patches (Gobran and Clegg 1996).

6.5.4.1 Mechanism of K Solubilization

The mechanisms for KSMs to solubilization of K are by: (i) lowering of pH or (ii) enhancing chelation of the cations bound to K and (iii) acidolysis (decomposition of a molecule under the influence of an acid) of the surrounding area of microorganism. The K-solubilizing microorganisms release of organic acids and protons that lowers the pH (Uroz et al. 2009; Zarjani et al. 2013; Parmar and Sindhu 2013; Verma et al. 2017; AL-Hamandi 2020). Organic acids produced by the rhizospheric microorganisms cause acidolysis either by dissolving the mineral K or by chelating both Si and Al ions associated with K minerals (Römheld and Kirkby 2010; Badge and Adlakha 2019). Thus, protonation and acidification lead to the release of K ions from the mineral K (Goldstein 1994). Organic ligands complex with silicic acids in solution and reducing solution silicon concentration which helping in further chelation.

6.5.4.2 Molecular Genetics of K Solubilizing Bacteria

K uptake by microbes is accompanied by three different types of K transporters Trk, Kdp, and Kup among them *Escherichia coli* K-12 contains two major types of K^+ uptake systems (Trk and Kdp) and one minor K^+ uptake system (Kup) (Schleyer and Bakker 1993; Badge and Adlakha 2019). Kdp system facilitates uptake of K^+ with high affinity (Siebers and Altendorf 1993; Silver 1996; AL-Hamandi 2020). Trk is a multi-component complex widespread in bacteria containing TrkH and TrkG that help in rapid uptake of K with a low affinity for K^+ (Dosch et al. 1991; Verma et al. 2017; Badge and Adlakha 2019), whereas *Bacillus subtilis* contains the Ktr gene involved in K uptake. The Kup transporter isolated from E. coli has also similar affinity for Rb^+ and Cs (Bossemeyer et al. 1989).

6.5.5 Micronutrients Dynamics

Metal solubility in rhizodeposition has been attributed to three mechanisms:

Adsorption of metals by roots (Lasat et al. 1996) and subsequent trans-location of metal from roots to the shoots (Shen et al. 1997; Chen and Cutright 2001); Increasing availability of metals in the rhizodeposition resulting from modification of pH, redox potential and release of organic acids and/or chelation by roots (Hinsinger 2001; de Santiago et al. 2019); and Foraging of metals by the roots, involving preferential allocation of root biomass into regions of metal enrichment (Schwartz et al. 1999).

6.5.5.1 Trace Metals Solubilization by DOM

Dissolved organic matter is a complex mixture of many molecules that passes through a 0.45-mm filter. They can strongly bind heavy metals such as Cu, Pb, Cd, Zn and Ni, and play an important role in controlling trace metal speciation in soil (Christensen and Christensen 1999; Kaiser et al. 2002; Nolan et al. 2003). DOC in soils may facilitate the release of adsorbed heavy metals from the solid phase to the soil solution as metal–DOC complexes (Kim et al. 2010).

6.5.5.2 Trace Metals Solubilization by Organic Acids

The exudation of OAAs by plant roots had a strong impact on the cation concentrations in the rhizodeposition solution. The given soil condition and solubility of metals determine the complexing capacity of organic acids (Dessureault-rompr'e et al. 2008). But in general under a given condition complexation follows the order. $Pb^{2+} > Cu^{2+} > Zn^{2+} > Cd^{2+}$ (Kim et al. 2010). The change is more pronounced in case of NO3- and NH_4^+ as their absorption results in efflux of OH^- and H^+, respectively, thereby altering the pH.

6.5.5.3 Fe Solubilization in Rhizodeposition

Fe in rhizosphere is solubilized by three mechanisms:

Acidification through proton extrusion and organic acid secretion, Chelation through secretion of complexing molecules with variable affinity for iron (phytosiderophores, siderophores, phenolics and carboxylic acids), and Reduction through secretion of compounds characterized by reducing properties or through the expression of a membrane-bound reductase activity. On the basis of mechanism utilized by plants (Fig. 6.9), they are classified into two groups:

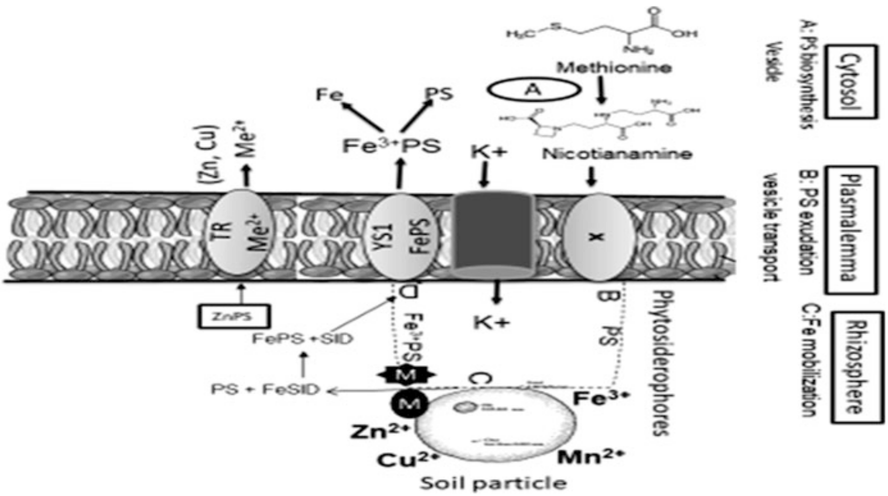

Fig. 6.9 Overview of different physiological mechanisms of improvement of Rhizodeposit in Fe and micronutrients uptake by plants

- *Strategy I plant:* In this type of plants Fe(III) is solubilized usually by rhizodeposition acidification, followed by complexation with chelating compounds and subsequent reduction of Fe(III) to Fe(II) which plant takes up by the roots through a transporter that have high affinity for Fe(II) (Eide et al. 1996; Zanin et al. 2019). Under Fe stress condition the plasma lemma H^+-ATPase is activated and rhizodeposition is acidified (Bienfait et al. 1989; Alcántara et al. 1991) followed by a concomitant release of phenolic acids (Olsen et al. 1981; Marschner et al. 1986) and carboxylates for Fe(III) complexation(Jones et al. 1996; Ohwaki and Sugahara 1997) and also for Fe(III) reduction in the rhizodeposition (Römheld and Marschner 1983). Dicotyledonous plants and non-graminaeceous monocotyledons (Römheld 1987; de Santiago et al. 2019) are typical example of this group.
- *Strategy II plant:* Under Fe deficient condition, graminaeceous plants release large amounts of non-proteinaceous amino acids, i.e. phytosiderophores predominantly from sub-apical root zones (Marschner et al. 1986), which have the capacity to chelate effectively Fe(III) (Tagaki et al. 1984; Murakami et al. 1989). The Fe(III)-PS chelates are stable at high soil pH levels >7(Treeby et al. 1989; Tagaki 1990; Zanin et al. 2019).
- As a result of high affinity of PS for Fe(III) to form complexes chelation with Ca^{2+}, Mg^{2+} and Al^{3+} is minimized (Ma and Nomoto 1996). However, recent studies have showed that sulphate supply increases phytosiderophores mediated Fe uptake (Zuchi et al. 2012) but phosphate applied as fertilizers at high rates may inhibit PS-promoted Fe(III) dissolution, mainly by displacement of PS from the

surface of Fe hydroxides (Hiradate and Inoue 1998). Grasses are typical example of this group (Romheld 1991).

6.6 Rhizodeposition Managements Strategies

From the above discussions it is clear that rhizodeposition processes reflect integrated interactions among plants, soils and microorganisms in both natural and managed ecosystems. So, the management of rhizodeposition ecosystems and rhizodeposition processes toward sustainable development of the plant–soil system may be one of the most important approaches to enhance the utilization efficiency of nutrient resources and crop productivity in various cropping systems (Shen et al. 2009; Zhang and Shen 1999; Zhang et al. 2004; Henneron et al. 2020). The concept of rhizodeposition management can be described as manipulating and managing various components in the rhizodeposition ecosystems a. manipulation of crop and cropping system b. manipulation of root system c. manipulation of rhizonutritional environment d. manipulation of microorganisms. I would concentrate on some specific nutrients management like C, N, P, S, Fe and Zn.

6.7 Conclusion

Secreting bioactive phytochemicals in the rhizosphere as a carbon and energy resource for plant roots attracts numerous beneficial bacteria and helps improve the microbes' root colonizing ability, resulting in a mutually beneficial interaction between soil microbes and plant roots. Rhizodeposits, root exudates and root-border cells are the driving forces for rhizosphere plant development and biological control activities. Plant roots may alter the chemistry of the rhizosphere in different ways, such as the release and absorption of organic compounds, the exchange of gases relevant to the respiration of roots and microorganisms in the rhizosphere, and the release of water and nutrients from the roots. It is quantified mainly through tracer techniques such as carbon tracer technique, N15 labeling plants and dwell labeling technique however, experimental analysis indicated that cotton wick method is the best technique for quantification for field and greenhouse studies. Rhizospheric bacteria participate in the geochemical cycling of nutrients especially nitrogen, phosphorus and micronutrients as iron, manganese, zinc and copper, and determine their availability for plants and soil microbial community. Molecular techniques have broadened and revealed interactions between root and microbes in studies of the rhizosphere. Developing modern state-of-the-art technologies for studying the ecology of the rhizosphere would help better understand the function and application of the broad range of bioactive phytochemicals generated by microbes, influencing root colonization ability, plant growth promotion and biological control.

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Soil Indicators and Management Strategies for Environmental Sustainability

7

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Abstract

Increased interest in soil health and sustainability in recent years emphasized the need to identify indicators and adopt improved management strategies in agroecosystems. This chapter discusses selected biogeochemical indicators of soil health, their linkages with soil ecosystem functions, and management strategies to increase crop yields and enhance environmental sustainability. Soil organic matter (SOM) components, greenhouse gas emissions (GHG), and microbial community structures and functions provide critical information on soil health and sustainability. Management approaches that minimize soil disturbance, maximize soil cover, and increase plant and animal diversity can increase SOM storage, mitigate GHG emissions, and support soil microbial community proliferation. Crop rotation, cover cropping, and livestock integration in cropping systems should be promoted to improve soil health and agro-environmental sustainability.

Keywords

Conservation agriculture · Greenhouse gases · Soil organic matter · Soil health

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7.1 Background

Environmental sustainability refers to a wide range of global-scale issues, such as greenhouse gas (GHG) mitigation, climate change, and renewable energy, to the location-specific problems such as soil erosion, water management, soil quality, and air–water pollution. Soil degradation is the primary global issue affecting sustainable crop production, the environment, and the quality of life on the earth. Increasing global population and climate change further exacerbated the problem and emphasized the need for soil management practices that increase crop production while maintaining environmental quality. Soil carbon (C) sequestration has become a topic of interest to scientists and policymakers to deal with climate change because of its potential to reduce global warming and improve soil health. It involves the microbial transformation of organic residues into a refined product, adsorption in the inner layer of clay particles, and formation of organo-mineral complex or protection within soil aggregates for centuries to millennia (Johnson et al. 2007). Several factors, such as soil temperature, moisture, particle size, soil contact, and biochemical composition of organic residues, determine the decomposition rate. Soil C storage is greater in fine-textured soils than coarse-textured soils because fine particles have a high affinity to the charged organic compounds. Similarly, soils in temperate region store more C than soils in tropical regions due to reduced soil organic matter (SOM) decomposition under cold temperature.

Globally, soils store about 2344 Gt [1 Gigaton (Gt) = 1 billion ton] of organic C, but 8.7 Gt of the accumulated soil C is lost to the atmosphere via carbon dioxide (CO_2) emissions and affect the environmental sustainability (Stockmann et al. 2013). Soil microbial communities regulate the SOM cycling, soil C sequestration, and GHG emissions under various soil types, climatic conditions, and management practices (Ghimire et al. 2014, 2017; Thapa et al. 2021). Environmentally sustainable agriculture increases soil C inputs and mitigates GHG emissions to maintain a positive C balance. The net ecosystem C balance approach helps to understand C flow in agroecosystems; how photosynthetically fixed C enters the plant biomass, soil environment, and ultimately loses through soil respiration (Chapin et al. 2006). Recent approaches also integrate soil organic carbon (SOC), a proxy of SOM, to estimate net ecosystem C balance (e.g., Thapa et al. 2019).

Other factors determining environmental sustainability of agricultural systems include nutrient cycling and availability. While increasing N and P fertilization rates can enhance crop yields, crops often extract only half of the applied nutrients. The remaining nutrients in the soils are lost via leaching or in gaseous form to the atmosphere. Nitrification and denitrification of residual soil N produce N_2O, a potent GHG that has 265 times more global warming potential than CO_2 (IPCC 2014). The residual nutrients also contaminate surface- and groundwater through surface runoff and leaching, resulting in eutrophication and health hazard to humans and animals. Therefore, SOM dynamics and microbial community structure and functions, including GHG emissions, indicate agronomic and environmental sustainability. This chapter discusses the soil indicators and management practices to improve the environmental sustainability.

7.2 Indicators of Soil and Environmental Sustainability

7.2.1 Soil Organic Matter

Soil organic matter is a complex mixture of organic substances in different states of decomposition, including living plants, animals and microorganisms, dead roots and other recognizable plants litter, and a massive unidentifiable colloidal mixture of complex organic substances. The SOC comprises about 58% of the SOM. Soils contain approximately 5% SOM, out of which <5% is living organisms, <10% is fresh residue, 33–50% is decomposing organic compounds, and 33–50% is stabilized organic matter (humus). Plant tissue is the primary source of SOM, whereas the secondary sources are animals. Photosynthesis converts atmospheric CO_2 into simple sugars, celluloses, hemicelluloses, proteins, lignins, polyphenols, starches, fats, and waxes (Clapp et al. 2005), which upon decomposition provide energy and nutrients to soil organisms and other plants. Therefore, soil organisms, such as fungi, bacteria, actinomycetes, enzyme activities, and GHG emissions, determine agro-environment health and sustainability. The composition of decomposing residues, such as the proportion of cellulose, hemicellulose, proteins, lignin, polyphenols, simple sugars, starches, fats, and waxes, influences the rates of decomposition. Simple proteins such as amino acids decompose and release nitrogen to the soil, while complex proteins are more resistant to breakdown. Based on relative complexity and their susceptibility to microbial decomposition, SOM is divided into three major pools:

1. *The active pool* consists of easily decomposed materials with a turnover period of a few days to a few years (Fig. 7.1). It improves soil structure and minimizes soil erosion. Organic matter in the active pool has a C:N ratio of 15–30 and supplies N, P, S to plants and soil organisms. Active-pool SOM varies with amounts and quality of residues, decomposition rates, soil environment, climatic conditions, and microbial activity.
2. *The slow pool SOM* consists of organic materials that exhibit intermediate properties between the active and passive pool with a turnover period of 10–100 years. Organic matter in this pool has an average C:N ratio of 10–25. This pool includes the finest fraction of particulate organic matter high in lignin content and other slowly decomposable components.
3. *The passive pool SOM* consists of the recalcitrant products of organic matter decomposition and has a turnover period of 10–1000 years. Organic matter in the passive pool has an average C:N ratio of 7–10. The SOM in this pool has a high surface area and serves as a reservoir of nutrients. It is essential for the long-term nutrient balance in the soil, supporting the sustainability of the agroecosystems.

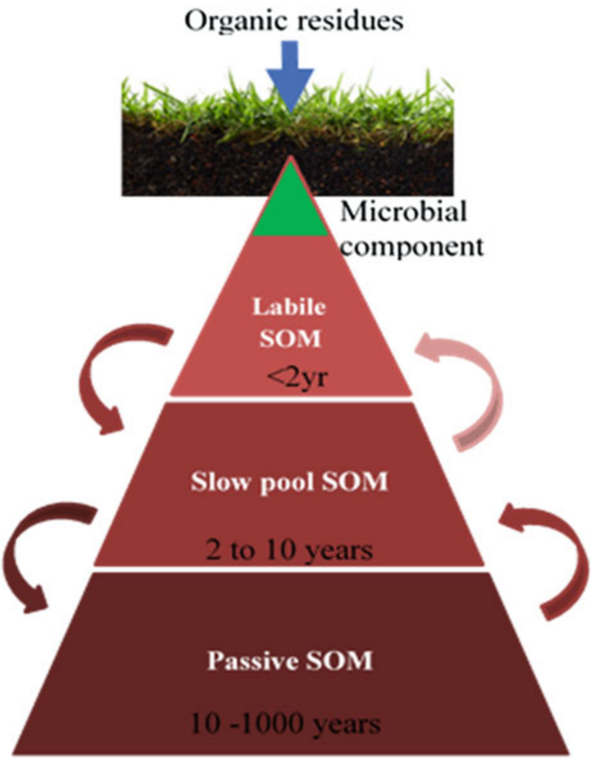

Fig. 7.1 Soil organic matter fractions and their residence time in soils (modified from Ghimire et al. 2020)

7.2.2 Greenhouse Gas Emissions

Greenhouse gas emissions indicate C and nutrient flow in the environment. The radiation emitted from the sun strikes the earth's surface and is reflected back to the atmosphere. High GHG[CO_2, methane (CH_4), nitrous oxide (N_2O)] concentrations in the atmosphere block the solar radiation, causing an increase in global temperature. Conversion of forests and grasslands to agricultural lands, increase the atmospheric concentrations of GHGs. About 24% of total global GHGs are produced from agriculture, forest, and land-use change. In the case of CO_2, 11% of the total emissions are from land-use changes and forest sectors (Fig. 7.2) (IPCC 2014). Agricultural practice should aim to increase the atmospheric CO_2 sink and make the system a C-negative (reduced net atmospheric C concentration) or C-neutral to improve agronomic productivity and environmental sustainability.

Although CO_2 is the major contributor to GHG, the global warming potential of CH_4 and N_2O are 21 and 310 times, respectively, higher than that of CO_2 (IPCC 2014). The primary sources of CH_4 are rice fields and livestock-integrated crop fields. The livestock sector contributes CH_4 from enteric fermentation in the animal rumen and manure (Asgedom and Kebreab 2011). In crop fields, CH_4 emissions depend on moisture level, N content, growing season, and soil aeration (Johnson

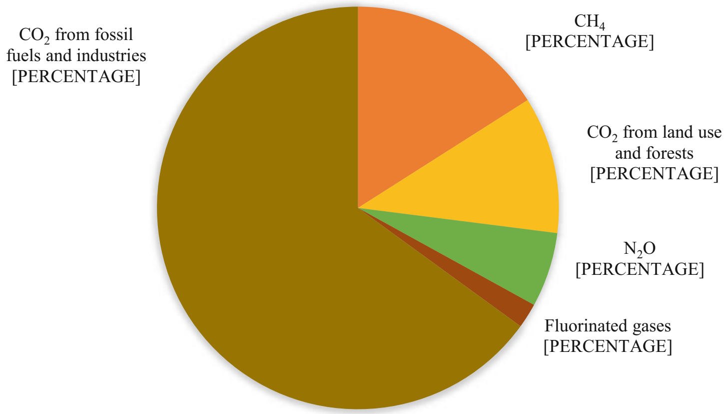

Fig. 7.2 Global greenhouse gas emission by gas species (IPCC 2014)

et al. 2007). For example, frequent draining of water from the rice field, sulfur-containing fertilizer application, and low N fertilizer rate reduce the CH_4 production. Drainage increases the number of methanotrophic soil bacteria, consumes CH_4, and reduces their emissions.

The N_2O contributes to 6% of the total global GHG emissions (IPCC 2014). The agricultural and non-agricultural land produces 4.2 and 6 Tg N year^{-1}, respectively, which in combined is 62% of the total N_2O emissions (Cameron et al. 2013). The agricultural N_2O emission depends on soil microbial processes, the aerobic transformation of ammonium to nitrate (nitrification), as well as the anaerobic transformation of nitrate to N_2 gas (denitrification). The incomplete nitrification or denitrification during the microbial decomposition releases N_2O (Metay et al. 2007; Snyder et al. 2009). Soil microorganisms get food from crop residues or N-fertilizer. Therefore, high N-inputs lead to increased N_2O emissions. In a study comparing chemical vs. organic sources of nutrients, greater N_2O emissions were observed from manure applications than the conventional fertilizers such as ammonium nitrate and urea (Ghimire et al. 2017). Management practices that improve N-use efficiency such as conservation tillage, split-N applicatin, and crop rotation can reduce GHG emissions from agro-environments (Sainju et al. 2012).

7.2.3 Soil Microbial Community Structure and Functions

The microbial community regulates soil C and nutrient cycling by releasing extracellular and intracellular enzymes. High fungi, Gram-positive bacteria, and protozoa populations indicate more resilient soil conditions and sustainable agro-environment. Reduced soil disturbance, crop rotation, and cover cropping increased microbial community abundance and enzyme activities (Ghimire et al. 2014, 2019; Thapa et al. 2021). This was possibly due to increased microbial substrate availability and the development of a favorable soil environment for their proliferation. Increased residue inputs through crop residue mulching or incorporation also increase microbial activity, supporting soil health and sustainability.

Decomposition is an enzymatic oxidation process involving the breakdown of large organic molecules into smaller components. Several enzymes are involved in the decomposition process in which long-chain organic polymers are broken down into short chains and ultimately individual subunits. Microorganisms produce specific enzymes crucial for breaking chemical bonds between organic molecules. For example, enzyme cellulase breaks down cellulose and starch, while β-glucosidase, involved in the final step of cellulose degradation, produces simple sugars for soil microorganisms (Bandick and Dick 1999). The enzyme β-glucosaminidase hydrolyzes chitin, degrading amino sugars and releasing mineral N in soils (Ekenler and Tabatabai 2002). Similarly, alkaline and acid phosphatase catalyzes the hydrolysis of organic phosphates into inorganic P. Only a few microorganisms, mainly fungi, can breakdown lignin molecules, which contain several interlinked phenol structures, and play a vital role in the soil environmental sustainability through increased soil C sequestration.

7.3 Management Approaches for Improving Environmental Sustainability

Agricultural management practices affect the soil and environmental factors (e.g., temperature, moisture, aeration, pH, nutrient availability) (Rakshit et al. 2017) and thereby GHG emissions, microbial community, SOM dynamics, and nutrient cycling. The following sections discuss crop and soil management approaches affecting agro-environmental sustainability.

7.3.1 Conservation Tillage Systems

Tillage involves physical disturbance of the upper soil layers for various purposes, including seed germination, establishment, growth, and development. Tillage helps in weed control and mixing of crop residues, fertilizers, or other amendments with soil. However, it exposes soil aggregates to environmental stressors such as high and low temperature, precipitation, and increases aggregate disruption (Wei et al. 2014). Intensive tillage break soil aggregates and expose large amounts of labile organic matter to microorganisms, stimulating decomposition (Zuber et al. 2015). Rapid turnover of aggregates inhibits SOM formation and stabilization within microaggregates that have a longer residence time in the soil (Six et al. 1999). Intensive tillage also stimulates microbial activity and produces a flush of CO_2 (Zuber et al. 2015). The CO_2 emissions rate is directly proportional to the extent of disturbance (Johnson et al. 2007).

Conservation tillage systems minimize soil disturbance and increase surface residue cover. Minimizing soil disturbance improves soil aggregation and the

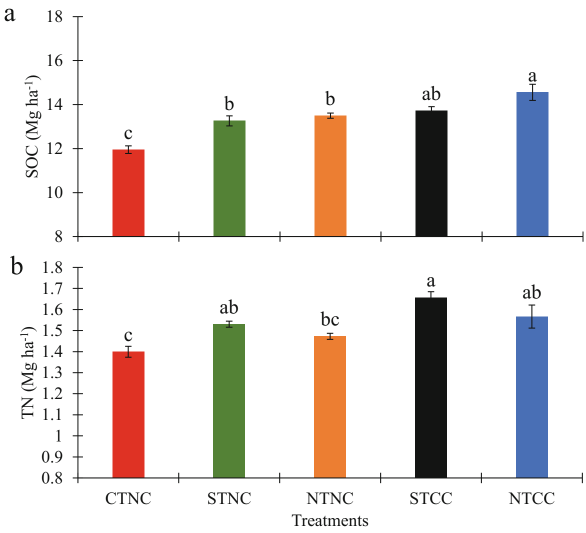

Fig. 7.3 Soil organic carbon (SOC) (**a**) and total nitrogen (TN) (**b**) under different cropping systems. Different lowercase letters accompanied by bars represent a significant difference between treatments ($p \leq 0.05$). *CTNC* conventional tillage without cover crops, *STNC* strip-tillage without cover crops, *NTNC* no-tillage without cover crops, *STCC* strip tillage with cover crops, and *NTCC* no-tillage with cover crops (Thapa et al. 2019)

physical protection of SOM. Improved soil structure increases soil fertility, residue inputs, microbial proliferation, which further reinforces aggregation. More residue on the soil surface under no-tillage protects soil from erosion, discourages the rapid decomposition of plant residues, and maintains high surface SOM. A recent study reported an increase in soil C storage with reduced-tillage and increased residue inputs through cover cropping (Fig. 7.3). The conservation systems mitigate GHG emissions by balancing the CO_2-C sequestration with the GHG equivalent of N_2O and CH_4 release, making the net GHG emission negative or neutral (Metay et al. 2007). Reducing tillage minimizes microbial activity by avoiding contact between soil microorganisms and crop residues, which may lower the N_2O and CO_2 emissions (Sainju et al. 2012). However, reduced-tillage systems also increase soil moisture, thereby more soil C and N mineralization and loss (Fan et al. 2018). Farmers adopt a continuous no-tillage approach to avoid the contact between crop residues and high organic C containing soil surface with microbial community, which ultimately protects SOM and improves environmental health and sustainability.

7.3.2 Crop Residue Addition and Surface Mulching

Crop residues increase microbial activity, nutrient cycling, and SOC accumulation (Martens et al. 2005). Crop residues provide a food source for microorganisms and support their growth. Residue cover also maintains cold soil temperature and reduces CO_2 and N_2O emissions, with significantly lower emission under stover retained than removed systems (Fan et al. 2018). The contrasting effects of surface mulching are observed in dryland cropping systems, where crop residues conserve soil water to

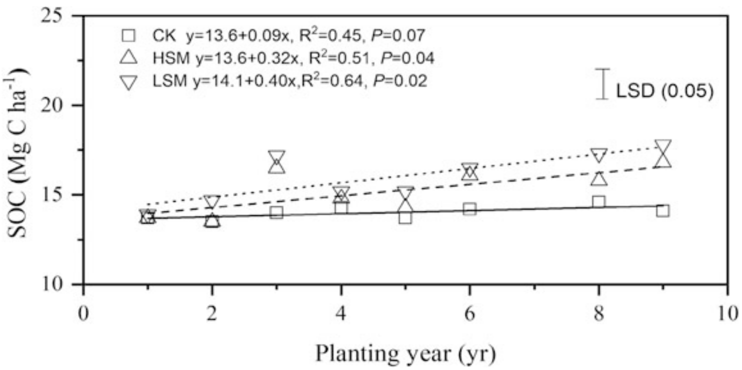

Fig. 7.4 Soil organic carbon (SOC) at 0-10 cm depths from 2009 to 2017 under straw mulching. CK = no mulching, HSM = wheat straw mulching at 9.0 Mg ha^{-1} during the winter wheat growing season, and LSM = wheat straw mulching at 4.5 Mg ha^{-1} during the winter wheat growing season. Years 1–9 represent 2009–2017 (modified from Wang et al. 2018b)

Table 7.1 Soil bacterial and fungal diversity (Shannon index) and richness (Chao index) with no mulching (CK), straw mulching (SM), and plastic film mulching (PM) at 0–10, 10–20, and 20–40 cm soil depths

Soil depth (cm)	Treatment	Bacteria		Fungi	
		Shannon index	Chao index	Shannon index	Chao index
0–10	CK	10.5a[a]	7575a	3.50a	747a
	SM	10.6a	8162a	3.51a	694a
	PM	10.2b	4699b	3.91a	691a
10–20	CK	10.3a	6671ab	3.74b	629b
	SM	10.6a	8006a	4.13a	852a
	PM	10.2a	4805b	4.18a	714a
20–40	CK	10.3a	7341a	3.03b	460b
	SM	10.2a	6494a	4.06a	576a
	PM	10.2a	3640b	3.98a	621a

[a]Numbers followed by different letters within a column and depth are significantly different at $P = 0.05$ by Duncan's multiple range test (adapted from Fu et al. 2019)

support crop production. A study reported straw mulching increased wheat grain yield and water use efficiency by 13–25% (Chakraborty et al. 2010). In the Loess Plateau of China, Wang et al. (2018a) reported an increase in precipitation storage efficiency at wheat planting by 3–4% and 13–16% with straw mulching. Straw mulching also adds organic inputs and increases soil organic matter (Wang et al. 2018b) (Fig. 7.4). Straw mulching enhances soil microbial biomass and changes microbial community structure due to increased carbon substrate availability. Soil microbial biomass carbon at 0–20 cm was greater with straw mulching at 9.0 Mg ha^{-1} in a wheat field (Wang et al. 2018b). Straw mulching did not affect bacterial diversity and richness but enhanced fungal diversity and richness compared to no mulching in subsoil layers (Fu et al. 2019) (Table 7.1). As improving soil health and quality is essential to sustain long-term crop yields, straw mulching can maintain dryland soil quality and crop productivity.

7.3.3 Cover Cropping, Crop Rotation, and Diversification

Crop types and management practices alter soil temperature, soil water storage, and evapotranspiration, the major drivers of SOC storage and GHG emissions, in agricultural systems (Sainju et al. 2012). Cover crops can benefit cropping systems by improving soil aggregation, water infiltration, SOC content, nutrient holding capacity, and microbial diversity (Muhammad et al. 2019; Ghimire et al. 2019; Thapa et al. 2021). High-quality residues (low C:N ratio) decompose faster, release mineral N in the soil, and favor greater N_2O production, whereas low quality (e.g., non-legume) cover crop residues uptake N from soil and minimize the N_2O emissions (Muhammad et al. 2019). Cover crops increased N_2O emission in 40% of studies and decreased in 60% of studies included in the meta-analysis (Muhammad et al. 2019).

In arid and semiarid regions, where continuous cropping is not possible, crop rotations include long fallow periods between crops to increase soil water storage and reduce subsequent crop failure risk. However, the long fallow period accelerates

Table 7.2 Orthogonal contrast analysis of soil microbial community structure and enzyme activities under various cover cropping treatments in 2017 and 2018

Variable	Contrast 1. Fallow	Cover crops	Δ	Contrast 2. Monoculture	Diverse-mix	Δ
	nmol g^{-1} soil		(%)	nmol g^{-1} soil		(%)
Microbial community size	68.4b	82.7a	21	81.8b	91.7a	12
AMF[a]	3.71b	5.76a	55	5.67b	6.83a	20
Saprophytic fungi	30.2b	36.7a	22	36.3b	40.9a	13
Total fungi	34.0b	42.5a	25	42.1b	47.7a	13
Gram-positive bacteria	17.5b	20.5a	17	20.3	22.3	10
Gram-negative bacteria	4.36	4.95	14	4.80b	5.57a	16
Actinobacteria	11.4b	13.4a	18	13.3	14.5	9
Total bacteria	33.2b	38.8a	17	38.4	42.3	10
Protozoa	1.31	1.44	10	1.46	1.69	16
Gram-positive/gram-negative bacteria ratio	4.01	4.44	11	4.72	4.05	−14
Fungi/bacteria ratio	1.02	1.09	7	1.09	1.13	4
	Mg PNP kg^{-1} soil h^{-1}			Mg PNP kg^{-1} soil h^{-1}		
Alkaline phosphatase	201	215	7	212	227	7
β-Glucosaminidase	16.7	18.7	12	18.7	18.2	−3
Combined enzyme assay	134b	167a	25	155b	185a	19

[a] *AMF* Arbuscular mycorrhizal fungi, *PNP* *p*-nitrophenol. Diver mix = mixture of oat, barley, Austrian winter pea, hairy vetch, canola, and forage radish (modified from Thapa et al. 2021)

wind and water erosion, SOC loss, and decrease crop production. Increased total crop production through crop intensification typically increases residue C inputs and thereby SOC accumulation. Cover cropping in the fallow period increases microbial community size and individual microbial groups (Thapa et al. 2021) (Table 7.2). The massive production of root residues and rhizodeposits through cropping systems diversification increases C sequestration when production exceeded decomposition. Ghimire et al. (2019) reported an increase in SOC components through cover cropping. Increased litter inputs and SOC storage can improve plant water availability, nutrient cycling, and soil C sequestration. In previous studies, surface residue cover reduced soil temperature, mitigated GHG, and increased SOC stock (Thapa et al. 2019; Nilahyane et al. 2020), indicators of sustainability.

7.3.4 Livestock-Integration in Cropping Systems

Livestock production is an integral part of agriculture. Livestock urine and manure provide nutrients to crops. Water-soluble SOC present in the manure, especially in cattle slurries, significantly increases the denitrification potential and N_2O emissions. Liquid manures have higher potentially mineralizable C and N contents, the nutrients for denitrifiers, than solid manure. Long-term stockpiling of livestock manure is recommended for improved crop production but can lead to greater CH_4 emissions during stockpiling. While there are high CH_4 emissions from manure stockpile, composted manure application increases SOC storage and improves crop production. An integrated assessment of livestock-integrated agriculture is recommended for understanding their role in agronomic and environmental sustainability. In a study, Acharya et al. (2019) reported an increase in SOC and total N with a higher rate of composted dairy manure application (Fig. 7.5), a significant component of the agro-environmental sustainability.

Grazing animals excrete about 85–90% of consumed N (Cameron et al. 2013). However, extensive grazing keeps the soil N content low because of crop uptake and immobilization of N. Extensive grazing at a high stocking density could result in a greater deposition of dung and urine, which increases GHG emissions. Oertel et al. (2016) reported that sheep-grazed pasture had less N_2O emissions than cattle-grazed, and non-grazed pasture emitted significantly less N_2O than grazed. Higher N_2O emissions from cattle-grazed pasture could be due to a large amount of N-concentrated excreta of cattle disposed around the pasture (Chadwick et al. 2018). The N_2O emission from the grazing fields depends on the stocking rate, pasture quality, manure quantity, precipitation, and SOC level (Johnson et al. 2007). The use of nitrification inhibitor in the grazed pasture soils could reduce N_2O emission by up to 81% from the livestock excreta patches (Cameron et al. 2013). Due to a well-developed root system and networking structure, pasture lands accumulate more SOC in the profile than croplands (Stockmann et al. 2013). In addition, grazing animals in crop fields can increase SOC and N accumulation. Light grazing increases SOC storage by stimulating plant biomass production (e.g., Frank et al. 2016), while grazing at high stocking density may deplete SOC and nutrients.

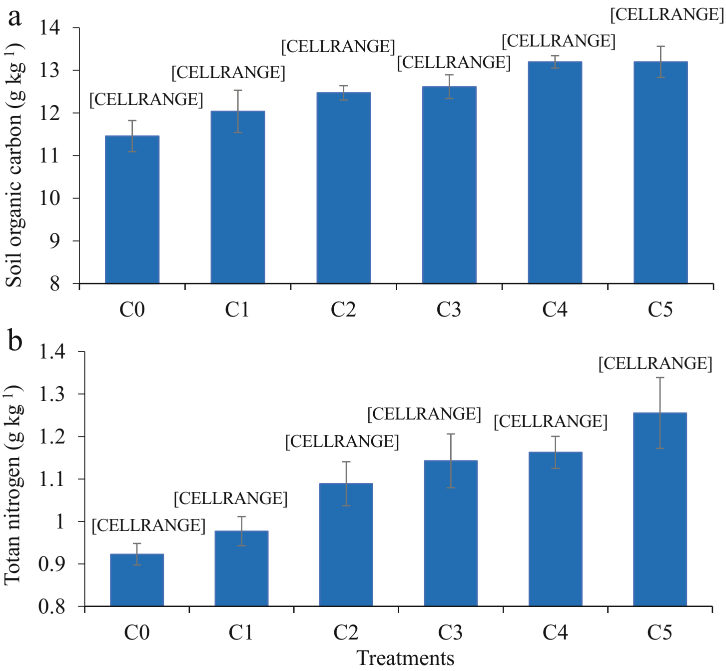

Fig. 7.5 Soil organic carbon (**a**) and total nitrogen (**b**) at sorghum biomass harvest under different rates of compost. Treatments C0, C1, C2, C3, C4, and C5 represent compost rates of 0, 6.7, 13.5, 20.2, 26.9, and 33.6 Mg ha^{-1}, respectively. Bars above the mean are mean ± standard error ($n = 4$). Means accompanied by different lowercase letters are significantly different at $p < 0.05$ in the Tukey Test (adapted from Acharya et al. 2019)

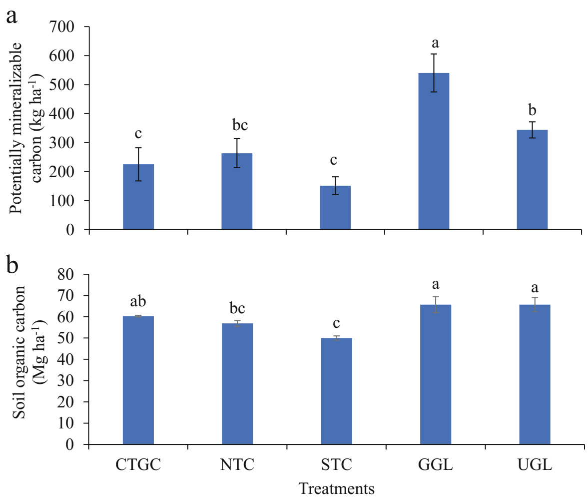

Fig. 7.6 Potentially mineralizable carbon in surface 0–20 cm (**a**) and soil organic carbon in 0–80 cm soil profile (**b**) under croplands and grasslands. *CTGC* conventional-tilled winter grazed cropland, *NTC* no-tilled cropland, *STC* strip-tilled cropland, *GGL* grazed grassland, and *UGL* ungrazed grassland. Different letters accompanied by bars indicate a significant difference between management systems ($P \leq 0.05$)

High microbial activity, soil C mineralization, and SOC storage with livestock grazing was observed in cropland and comparable SOC with and without grazing in grasslands (Fig. 7.6). Soil microbial biomass, specifically fungal community and gram-positive bacteria, also increased with grazing (Ghimire et al. 2019). Comparing grazed and ungrazed sites, Derner et al. (2006) reported 24% greater whole-ecosystem C storage (soil+plant) in grazed grasslands than ungrazed grasslands in a shortgrass community typically present in the semiarid Central and Southern Great Plains regions of the USA. The magnitude of difference between grazed and ungrazed systems was not observed in croplands (Ghimire et al. 2019), possibly because livestock was grazed only for 3 months during winter.

7.4 Conclusion

Agro-environmental sustainability can be improved by increasing SOC, mitigating GHG, and supporting microbial community proliferation. Conservation system that minimizes tillage and integrates crop rotation or cover cropping improves agro-environmental sustainability by increasing SOC, mitigating GHG emissions, and supporting microbial community proliferation. Proper tillage, cropping practices, cover cropping, residue management, livestock manure management, and livestock integration strategy can increase SOC storage, increase microbial activity, and reduce GHG emissions. Therefore, adopting conservation agricultural practices such as reduced tillage, cover cropping, crop rotation, and diversifying cropping system is recommended to maximize ecosystem services such as nutrient balance, soil C sequestration, and GHG mitigation to improve the agronomic and environmental sustainability.

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Conservation Agriculture in Reshaping Belowground Microbial Diversity

8

Puja Singh, Siddhartha Mukherjee, Niharendu Saha, Sunanda Biswas, and Biswapati Mandal

Abstract

Microbial diversity and their activities are the key indicators of soil health and quality as it responds quickly towards the alteration performed in the soil environment through crop management practices. Modern agriculture is input intensive and highly torturous in nature thus becoming threats not only to microbial world but to whole environment. Thus, it is high time for the farmers and agriculturists to address the issue of environmental sustainability along with sustained crop productivity of management practices to ensure the future food security goal. Approach of conservation agriculture (CA), in this context, in terms of low mechanical disturbance, crop rotation, retention of diverse crop residues and release of diversified chemical compounds as rhizo-depositions to soil and maintaining a protected, cosy habitat for microbes is well ahead. This chapter will provide a comprehensive summary of knowledge regarding the potentiality of CA to regenerate and conserve top soil by restoring microbial diversity and ecosystem services. Special emphasis is given to service providing keystone microorganisms along with their associations with plants to perpetuate the sustainability in low input-based CA systems. Further, challenges and relevant questions for proper understanding of CA ecology have been discussed. A set of management strategies including GPS/GIS enabled precision agriculture and designer microbes are suggested as promising solution to conserve keystone

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microorganisms under CA. Few outstanding and thought provocation questions are raised in the perspective of crop yield and profits derived out of diversity based ecosystem services for future course of biodiversity research under CA. Outcome of such study will be helpful to the farmers for adopting CA, particularly, in tropic and subtropical countries where agriculture is greatly relying on the benefits derived from plant–microbes interactions.

Keywords

Substrate diversity · Habitat · System stability · Demographic predictability · Keystone species · Oligotrophs · Copiotrophs

8.1 Introduction

Conservation agriculture (CA) is a regenerative approach of agricultural development triggering the indigenous inherent potentialities of the system by biological entity of soil. It is an ecologically intensified nature/semi nature-based alternative that complements or partially replaces external inputs with production-supporting ecological processes run by diversified life forms in soil to sustain crop production (Kleijn et al. 2019). Of them, microbial lead surpasses the other lives in soil. This overwhelmed phenomenon in CA has been documented by the contemporary workers (Duru et al. 2015) with the explanation of having huge abundance of microbes with profuse diversity in CA soil (Schmidt et al. 2018). Package of practices in CA enhances a range of regulatory and supporting ecosystems services with the assistance of diversified microbial load. So, scientists, land care manager and policy makers are advocating such ecological intensified agriculture through a greater reliance on biodiversity and ecosystem services. But, the intricacy of microbial diversity and function leading to continuous support of soil for sustenance of crop production is poorly documented (Onen et al. 2020). This may be due to poor understanding of soil ecology created under CA and associated microbial responses. Residue retention, crop rotation and reduced tillage mandatory to CA intensify carbon (C) sequestration and its stratification, improve soil structure and stability, increase moisture retention, create microclimate at residue–soil interface, restore habitat, augment substrate diversity, stabilize ecosystem, create heterogeneity and above all reduce demographic stochasticity to enhance microbial intensification with low species extinction risk. In this context, a thorough discussion was made on the mechanisms of rejuvenating the CA system with the sustenance of microbial diversity.

CA aimed at making nutrient availability by internal cycling employing the specific group of microorganisms and their interactions at low nutrient status as there is a huge redundancy among microorganisms in soil to perform similar function (Banerjee et al. 2016). In this context, the concept of real performer, master minds and core functional microbes well adapted at low nutrient concentration may be of more appropriate than total microbial load to understand the capacity of soil to elaborate continuous support to crop plants under CA. This mastermind microbe is the keystone that performs the core function of soil by influencing the associated fellow microbes and surrounding soil environment. Even they remain unaffected and elaborate disproportional function under different degrees of agricultural practices (Griffin et al. 2019). Thus, a hypothesis, viz. keystone microbial species are well conserved in CA induced microclimate, is put forward. Ecologically narrow clad of microorganisms of agricultural low redundancy including cellulose decomposing microorganisms, free-living N-fixing bacteria, phosphate solubilizing bacteria and arbuscular mycorrhizal fungi (AMF) are hypothesized as keystone for delivering essential services to soil under CA (Box 8.1). Dominance of those keystone species are very often reported under CA over conventional high input-based agriculture which is assumed to be sub-optimal in respect of biodiversity and ecosystem functioning (Paine 1995). But, identification of cropping system/s supporting and restoring keystone species and their sensitivity to management is the greatest challenge (Box 8.2) to adopt under field conditions. Furthermore, integration of elite keystone species in management strategies has to be tackled for prescribing good crop husbandry in CA. Key on-field practices that can improve belowground diversity and ecosystem functions are minimization of tillage, use of cover crops, increasing the diversity of the number of crops in rotation or mixed cropping. CA by virtue of its goodness augments and conserves wide array of microbes in soils. But excessive dependency on herbicides and phototoxic substances from residue decomposition are the inherent threat for declining diversity. Time lag for the establishment of diversity pools and manifestation of measurable functions is the main constrain for the adoption of CA by the farmers. In this context, management strategies for the augmentation of microbial diversity in CA systems are also the topic of discussion in this chapter (Box 8.3).

Predominant Keystone species under CA may be considered as good marker to the hands of land care managers and researchers for assessing soil health under CA. Furthermore, mass production of keystone microbes as bio-fertilizer, particularly, for conservation agriculture, will be a new direction in the field of agriculture. Tropical and subtropical countries where agriculture is largely dependent on plant–microbes interaction for nutrient acquisition will greatly be benefited by this approach. Concept of microbial diversity based ecological farming has its own limitation as because diversity–function relationship is indirect and the effect of diversity till date has not been explained in terms of crop yield and profits at farm level. So, the farmers are reluctant to accept this concept as their management tool in CA. Moreover, balance sheet on cost involvement to improve microbial diversity and profit derived from ecosystem services is currently absent. In this context, few outstanding questions are raised (Fig. 8.8) to be resolved during future course of research to make the concept farmer's relevant for the adoption of this technology for everlasting agriculture.

8.2 Belowground Microbial Diversity Under Conservation Agriculture

Huge biological diversity exists in the belowground food-web network under conservation agriculture of which arthropods have tremendous importance to initiate organic matter disintegration followed by microbial participation through the elaboration of wide array of enzyme to decompose complex organic compounds to easily utilizable fueling molecules. So, microbes are essential mediator for food and energy flow in soil system. Thus, the composition of microbial species (richness) and their relative abundance (evenness) are the yardstick for the liveliness of soil with sound heath to make the soil fit for supporting the plant communities with all necessary amenities. So, understanding the microbial diversity and their function under conservation practices is essential for biological management of soil in sustainable manner under low input-based agriculture.

Microbial diversity in the simplest form is different types of microorganisms residing in soil. Bibliographic antecedent reveals that microbial diversity is expressed by different authors in different ways either by culture dependent methods, *viz*. total cell count, bacteria:fungal ratio, G(+ve):G(−ve) ratio or by culture independent methods like structural, genetic and metabolic diversity. Abundance of signature fatty acid in microbial cell wall extracted from soils represents structural diversity while base sequence divergence and restriction fragment polymorphism of PCR amplified product determine genetic diversity of soil microorganisms. On the other hand, preferential carbon source utilization pattern by microorganisms represents metabolic diversity/metabolic finger printing or community level physiological profiling. Single approach for estimation of soil microbial diversity hardly explored the insight of soil microbial diversity due to soil heterogeneity, huge interactions and limitation of the methods. So, polyphasic approaches combining culture dependent and independent methods provide necessary information for microbial diversity. So, in this chapter, emphasis will be given to polyphasic approaches-based diversity analysis under conservation agriculture where microbial interaction and interference of organic matter to nucleic acid extraction are limiting factors. As soils under conservation practices are the rich repository of soil microbial diversity, so, there will be huge redundancy among microbial species for specific function. Thus, genetic diversity of microorganisms under conservation practices is of little importance. Rather, metabolic diversity which refers microbial metabolic versatility to obtain energy and nutrient from different substrates will be of prime consideration. Decomposition of crop residue retained in soil is an important function carried out by the microorganisms. This function is bestowed upon different decomposing microbial species. So, if few species become extinct or competitively expulsed, rate of decomposition, in general, will hardly be affected. On the other hand, if metabolic diversity is affected, decomposition of specific carbon compounds, e.g. cellulose and its derivatives contained in crop residues will drastically be reduced. Thus, energy fuelling to surrounding associated microbes will be affected. So, under conservation agriculture microbial communities tend to be oligotrophic life style strategy like cellulolytic microorganisms to make the system sustainable.

Soils are very sensitive to any agricultural practices due to the presence of living entity, particularly, myriads of microbial species. Fertilizer application, residue retention, cropping systems and tillage practices individually or in combination impact differently on microbial abundance, diversity and activity within microbial communities. Scientific literature shows that the application of conservation agriculture ultimately reorganizes soil microbial pools in different communities under the influence of various cropping systems, more under no-till than under conventional tillage. Management practices like fertilizer application, residue retention/incorporation, tillage practices and crop rotation may be comfortable to some microorganisms while discomfortable to others leading to shift in microbial community structure and activity of soil biota (Ndour et al. 2008). Heavy ploughing under conventional agriculture practices causes desiccation, soil compaction, reduced pore volume and its geometry as well as rapid mineralization of SOM. These lead to habitat destruction by faster declining of food (C and N) availability (Anderson et al. 2017), which ultimately causes extinction of several microbial species, loss of biodiversity and impairs agricultural sustainability (Phelan 2009). Adoption of conventional practices in long term imposes negative impact on soil biodiversity as discussed in Table 8.1. However, few authors argued that agriculture intensification first flourishes soil biodiversity before it collapses (Giller et al. 1997; Kuyper and Giller 2011). According to Kuyper and Giller (2011) accelerated carbon mineralization under deep ploughing results in increased microbial activity but the homogenizing of organic matter through depth reduces species richness.

Planned biodiversity under conventional agriculture (e.g. mono-cropping and use of high yielding varieties) results to reduction in crop diversification accompanied by

Table 8.1 Management practices under conventional farming and their influence on soil microbes

Practices under conventional farming	Way to disfavour microbial diversity
Indiscriminate use of chemical inputs	Rise in salt index of the soil which down regulates the soil ecosystem services and kills microbes Emission of GHGs (CO_2, CH_4, NO_X) due to fertilizer transformation to plant available form
Mono-cropping/monoculture	Induce fallow period thus reduce above-ground diversity and food supply to soil microbes consequently belowground diversity
Use of heavy machineries	Induce soil compaction and hamper porosity and aeration, reduce microbial mass and enzymatic activity
Ploughing	Mechanical disturbance and habitat destruction Homogenizing effect on SOM, nutrient loss Breaking tunnels connecting to microbes thus interrupting their food web
Avoiding residue returning to soil or residue burning	Dropping of SOM or SOC level in soil

Synthesized from Frankenberger Jr and Dick (1983) shift of belowground microbial communities in short term and diversity extinction (Kuyper and Giller 2011) in long-term practice. This is because as number and crop type decline, substrate diversity in term of supply of root exudates and litter to microbes are also lessen; causing less diversified microbial clad with poor functionalities under scarcity of diversified feeding materials. On the contrary, rotation with different crops under conservation agriculture harbours diversified microbial assemblages. Rhizo-deposits, dead root tissues, debris and moribund tissues of different crops having different chemical composition reorient the existing microbial communities to more diversified one. For example, cellulolytic bacteria are numerous in cereal rhizospheres, while PGPR and bacteria-feeding nematode under legumes (peas) (Liu et al. 2014). Practices of CA emphasize crop diversification, multiple cropping and crop rotation and fascinate different microbial communities by supplying diverse diet. Such practices not only avoid fallow period but in addition minimization of tillage and residue retention, reduce the extent of disturbance against harsh external environment. Therefore, it is argued that principles of conservation agriculture are capable of restoring above as well as belowground diversity. Maintaining such diversity is key to success to subsistence farmers who face the greatest risk from biodiversity losses under intensive agriculture as they solely depend on natural cycle and processes taking place in undisturbed soil. Hence the practices of intensive farming in other words are called "degenerative type" as impose threat to microbial diversity, aggravate global inequality and marginalize resource-poor farmers. Brussaard et al. (2010) suggested that regenerative approach or eco-efficient management of biodiversity could provide an escape from poverty (Table 8.2).

Cropping systems, tillage and residue management influence on soil biological properties and microbial count under conservation agriculture (Choudhary et al. 2018a, b, c; Rakshit et al. 2017). Residue management, whether mulched or incorporated is the determining factor for the abundance of microorganisms in soil irrespective of cropping system and tillage. In this context, residue mulching has edge over residue incorporation. Bacteria, fungi, actinomycetes and their activities are highly favoured by maize–wheat (MW) cropping system, more so by residue applied as mulch under zero tillage. Incorporation of residue results in uniform distribution of organic matter causing less availability of carbon to microorganisms, which, in turn, disfavours microorganisms. Fungi are more impacted as compared to bacteria under zero tillage with residue as mulch. Fungi by virtue of their higher biomass in soil utilize carbon more efficiently and, thus, flourish profusely in relatively undisturbed habitat under CA (Fig. 8.1).

Structural diversity as revealed by PLFA profiles was adopted to assess the soil microbial community composition under different field management (Fig. 8.2). No-tillage (NT) with residue application has positive effects on broad group of soil microbes. In this context, fungi harboured dominantly (Simmons and Coleman 2008), arbuscular mycorrihizal fungi (AMF), in particular (Wang et al. 2012) which was in agreement with other workers (Alguacil et al. 2014). Arbuscular mycorrhizal fungi (AMF) are important ecosystem service providing mutualistic keystone microorganisms under CA. They are considered important and useful in low-input

Table 8.2 Dominant microbial group under CT and factors favouring them under intensive farming

Predominating microbes	Reasons behind their abundance	References
Resilient microbes	They can resist extreme environments (e.g. ionizing radiation, ultraviolet light (UV) and desiccation) Intensification of tillage excludes out non-resistant or sensitive groups of microbes from soil	Makarova et al. (2007)
Aerobic microorganisms	Tilling offers better aeration capacity in plough layer compared to no-tillage system. Thus aerobic microbes, e.g. Deinococcus–Thermus, Gemmatimonadetes and Cyanobacteria are abundant under intensively ploughed soil. Deinococcus–Thermus (at phylum level) is reported to be two-fold more than ZT	Dorr de Quadros et al. (2012)
Bacteria > Fungi	Diversity of microbial diet under conventional farming is very low thus restricted decomposers who can synchronize their food need with slow release of nutrients grow here. Residue decomposition by bacteria prevails under intensive tillage while by fungi under no-till system	Mubekaphi (2019)
Copiotroph	High nutrient concentration because of fertilizer application favours copiotrophs	Sarrantonio and Gallandt (2003)
Non-mutualism/ independent microbes	Collapse of pore connectivity blocks microbial interaction and ultimately microbes surviving on mutualism or symbiosis. Thus independent microbial relation observed more frequently under modern farming than mutualism and symbiosis	Warmink et al. (2011) Ebrahimi and Or (2014)
	Restrict fungal hyphae to form connection between microbial communities present in rhizosphere and bulk soil and food webs formation by transporting C from fungi to facilitate bacterial movement	Fransson and Rosling (2014)

agricultural systems for enhanced sustainability (Altieri and Nicholls 2007). They are ecologically low redundant and highly sensitive to management practices (Jansa et al. 2002, 2003).

Box 8.1 Expected Keystone Species Under Conservation Agriculture

Keystone microbial species and the service provided under conservation agriculture	
Cellulose decomposing microorganisms (CDM)	
Assigned functions • Residue decomposition • Carbon transformation/sequestration • Nutrient release from residues for the replenishment of nutrients under low nutrient CA system • Supply of energy rich glucose molecule	Additional functions • Proto-cooperative interaction with free-living N-fixing bacteria by supplying energy rich glucose molecule required for N fixation • Plant growth promotion by elaborating

(continued)

Box 8.1 (continued)

to microbial communities for the survival and function in soil (ecological intensification)	phytohormones and other biologically active metabolites
Nitrogen fixing bacteria (NFB)	
Assigned functions • Enhancement of nitrogen by fixing atmospheric di-nitrogen to ammoniacal nitrogen for the use of microorganisms and crop plants for the biosynthesis of protein • Contribute 10–30 kg N/ha, helpful to replenish N requirement of crop under CA where N status is low	Additional functions • Production of phytohormones for the growth promotion of plant • Improvement of soil aggregation by the gummy substances/extra polysaccharides produced by the most of N-fixing free-living bacteria • Disease suppression by the production of antibiotics
Phosphorus solubilizing microorganisms (PSM)	
Assigned functions • Improve phosphorus availability by the solubilization of insoluble inorganic phosphate to replenish *P* content under low *P* status in CA system • Contribute 5–25 kg P/ha, helpful to replenish prequirement of crop under CA where *P* status is low	Additional functions • Production of phytohormones for the growth promotion of plant • Reduction of Al toxicity helpful for root growth • Regulate pH status of soil
Arbuscular mycorrhizal fungi (AMF)	
Assigned functions • Mobilizing limiting nutrients like phosphorus, zinc under reduced nutrient-based conservation agriculture • Improve soil aggregation by the production of glomalin for habitat reconstruction • Increase water holding capacity (WHC) of soil • Impart tolerance of crop plants against biotic and abiotic stresses by bringing about several changes in their morpho-physiological traits	Additional functions • Help plants' adaptability under stressful environment like salinity, drought, heat wave • Improve soil health and plant health • Affect stomatal conductance, leaf water potential, relative water content (RWC), PSII efficiency • Affect atmospheric CO_2 fixation by host plants, by increasing "sink effect" and movement of photo-assimilates from the aerial parts to the roots with yield maximization • Safeguarding the plants from fungal pathogens

Conventional tillage exerts strong negative impact on AMF communities, and selects for low diversified aggressive colonizers that likely have restricted benefit for the plant. On the other hand, CA based practices preferably select more beneficial AMF communities with higher abundance of spores and diversity of AMF (Jansa et al. 2002). Tillage and mineral nitrogen have reoriented AMF communities. AMF species composition drastically reduces in conventional tillage (CT) systems in combination with nitrogen fertilizer compared to NT systems with no fertilizer.

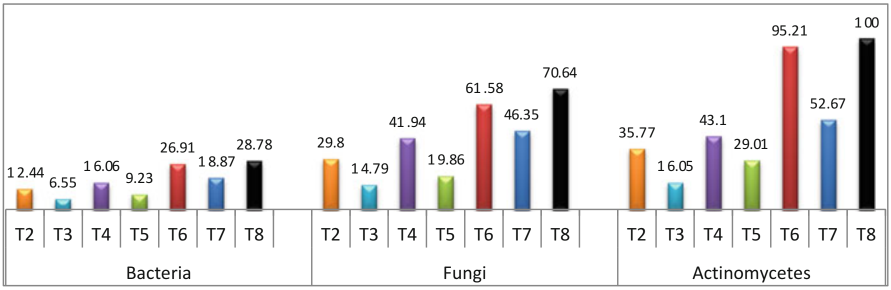

Fig. 8.1 Percent increase in microbial populations under different management practices (tillage, crop rotation and residue) over conventional after 3-crop cycles (Adapted from Choudhary et al. 2018a, b, c). Treatment details: T1 (control: RW/CT − R), T2 (RW/CT+Ri), T3 (RW/ ZT − R), T4 (RW/ZT + Rm), T5 (MW/CT − R), T6 (MW/CT + Ri), T7 (MW/ZT − R), T8 (MW/ ZT + Rm), where *CT* conventional tillage, *ZT* zero tillage, *R* residue i—incorporated, *m* mulched, *R* rice, *W* wheat, *M* maize. Result interprets that treatments T6, T7 and T8 offer edge over rest as the treatment combines the practices having stimulatory effect on soil microbes

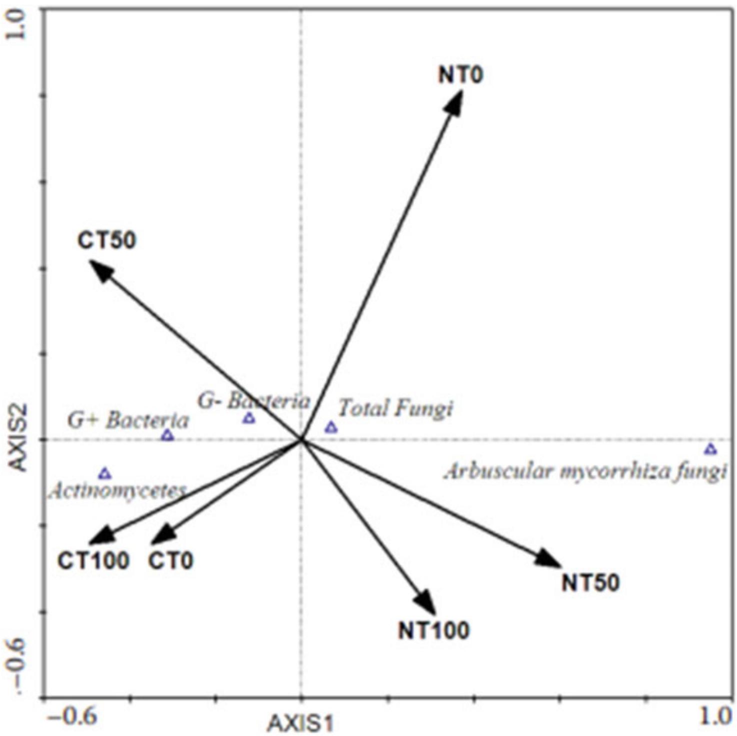

Fig. 8.2 Canonical correspondence analysis of soil PLFA profiles and different treatments (NT0, NT50, NT100 represent no-tillage with no residue (0%), 50% and 100% residue, respectively; CT0, CT50, CT100: conventional tillage with no residue, 50% and 100% residue, respectively; Adapted from Wang et al. (2012)

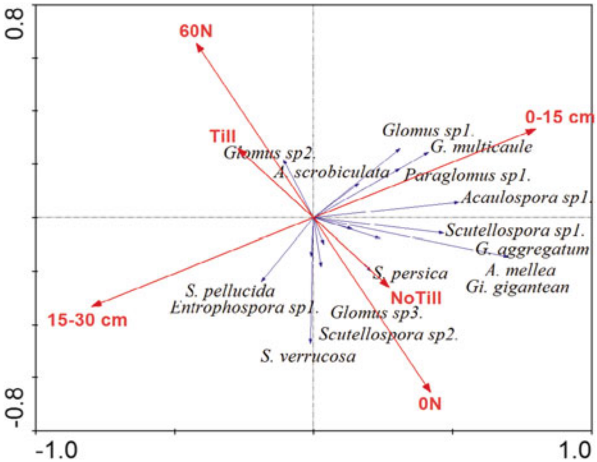

Fig. 8.3 Effects of tillage and N fertilization on the community composition (relative species abundances) of AMF in the field soil. Adapted from Muriithi-Muchane (2013)

Glomus becomes predominant under CT, whereas in NT species of *Scutellospora* dominated (Jansa et al. 2002). AMF are better adapted in surface soil then sub-surface (Muriithi-Muchane 2013). Increased AMF hyphal length (Kabir 2005) and root colonization (Castillo et al. 2006) are also reported in NT systems. Low AMF colonization, resulting in lower nutrient uptake and reduced yield, has also been shown in CT systems (Galvez et al. 2001). Tillage does not only disrupt the mycorrhizal network but affects mycorrhizal functioning (Kabir 2005) (Fig. 8.3).

Conventional tillage, on the other hand, significantly decreases soil fungi by physically disrupting their hyphal networks and/or by affecting soil moisture regime, resulting in a decreased fungal biomass. Bacteria, viz. G (+ve) bacteria, G (–ve) bacteria and actinomycetes are predominantly flourished under CT. G+ bacteria may be the dominant member adapted to CT because of its capacity to form spores to avoid different levels of stress created by CT operations.

Soil microbial properties under conventional and conservation practices not only vary with respect to microbial population and their activities but also with their community structure (Dorr de Quadros et al. 2012). Conventional and conservation practices distinctly facilitate completely different clads of microorganisms. While conventional tillage favours number of Proteobacteria such as Gemmatimonadetes, Cyanobacteria and Deinococcus–Thermus conservation practices, particularly no-tillage provides niche for Verrucomicrobia, Firmicutes, Crenarchaeota, Chlamydiae, Euryarchaeota and Chlorobi. Difference in microbial community structure under different crop management practices as reported by different researcher is depicted here (Table 8.3):

Limited mechanical disturbance under conservation agriculture improves aggregate stability (Mäder et al. 2002), which, in turn, improves soil's physical properties and resulted in protected microbial habitat (Lopes et al. 2016). It keeps microbes unstressed for performing their optimum functioning which is expressed in terms of improved microbial biomass and enzyme activities. Since the topsoil under CA receives huge residues used as food materials by microbes, quick response in

Table 8.3 Microbial community structure under different management practices

Taxonomic hierarchy	Location	Conventional tillage	No-tillage	Crop rotation/residue retention	References
Bacteria	South Brazil	*Gemmatimonadetes*, *Cyanobacteria*, *Deinococcus–Thermus*	*Verrucomicrobia*, *Firmicutes*, *Crenarchaeota*, *Chlamydiae*, *Euryarchaeota*, *and Chlorobi*	*Clostridium*, *Bacillus*, *Burkholderia*, *Bradyrhizobium*, *and Phenylobacterium*	Dorr de Quadros et al. (2012)
	Texcoco, Mexico	*Rhodobacterales* *Methylobacterium* *β-Proteobacteria* *Burkholderiales* *Lysobacter* *Rhodanobacter*	*Arthrobacter* *Flavobacteria* *Flavobacteriale* *Rhizobiales* *Myxococcale* *Rhodospirillales*	–	Ramirez-Villanueva et al. (2015)
	Karnal, India	*Alphaproteobacteria >> Acidobacteria-6*	*DA052(Acidobacteria) >> Alphaproteobacteria*	–	Choudhary et al. (2018a, b, c)
Fungi	Bernburg, Germany	*Rhizophagus* *Septoglomus* *Paraglomus* *Claroideoglomus* *Diversispora*	*Talaromyces* *Rhizophagus* *Septoglomus* *Entrophospora*	–	Sommermann et al. (2018)
	Dryland Pacific northwest (Idaho, Oregon and Washington)	*Chalara* *Glarea* *Mycosphaerella*, and *Ulocladium*	*Exophiala* *Humicola* *Exophiala* and *Humicola*	–	Sharma-Poudyal et al. (2017)
	Karnal, India	*Basidiomycota* and *Glomeromycota*	*Ascomycota Sordariomycetes*, *Dothideomycete*, and *Eurotiomy*	Sordariomycetes	Choudhary et al. (2018a, b, c)

microbial diversity and activity is mostly observed here. Such protected habitat also facilitates rapid multiplication, biomass production by microbes (Table 8.4) and increase in fungi: bacteria ratio (Drijber et al. 2000) (Table 8.5).

Oligotrophs like Acidiobacter, Planctomycetes, Verrucomicrobia are abundant under CA (Fig. 8.4) due to slow nutrient release, whereas high nutrient concentration because of fertilizer application favours copiotrophs under CP (Ramirez-Villanueva et al. 2015). Nature of residues determines types of microbial families predominant in soils. The relative abundance of Arthrobacter (Actinobacteria) and Bacillales was more than double when maize residue was applied and Actinomycetales when NDF (neutral detergent fibre) was applied.

Habitat heterogeneity in ditritusphere, rhizosphere, aggregatusphere, drilosphere and porosphere and fair amount of easily oxidizable C-sources coming from residue decomposition sequestered within the habitats along with the restricted oxygen mobility in those habitats make CA system congenial to harbour diversified N-fixing bacteria for efficient nitrogen fixation (Gupta et al. 2019). Conventional tillage reduces aggregation, reduces soil C and disrupts the soil pore network by which stubble decomposing organisms and N-fixing bacteria interact. As a result, non-symbiotic nitrogen fixing bacteria (NSNF) under reduced tillage is characteristically higher than in cultivated soils (Roper and Gupta 2016). However, there is huge time lag between biological changes in NSNF in response to adopting CA and measurable function manifested by this group of bacteria. Crop residues retained in soils under CA provide enormous amount of soluble carbon to free-living N-fixing bacteria by decomposing cellulose, hemicelluloses contained in residues. The availability of C as an energy source is critical for NSNF bacteria for their proliferation and function. As a result, rates of NSNF are proportional to the amount of crop residue and how quickly it is decomposed. Genetic profiling (*nif*-H gene sequencing analysis) of N-fixing bacteria in soils under cereal crops and under CA identified a diverse group of NSNF bacteria, but these varied according to region, soil type and environment and cereal crop varieties (Gupta et al. 2014).

Residue mulching influences the diversity of microorganisms and changes across season and depth of soil (Dong et al. 2017). Mulching during autumn favours more diverse bacterial and fungal communities than the without mulching at surface and sub-surface because mulching assures high quality substrates addition and upgrades micro-ecological environment that is more resilient to environmental fluctuation (Wu et al. 2009). In this context, maize residue is richer in carbonaceous substrate than rice, hence causes a shift in microbial community structure. This shift in community structure was illustrated by change in MBC:MBN ratio. Fungal predominant community is expected in soils receiving residues under RT as indicated by higher MBC:MBN ratio while bacteria under CT as due to lower MBC:MBN ratio. Low soil disturbance and residue retention at soil surface promote fungal growth as with the help of hyphae they can easily exploit the water and nutrients from small spaces in the soil that might be inaccessible to roots and stabilize larger soil aggregates by secreting sticky gel (Fig. 8.5).

In addition, fungi are efficient carbon utilizer and assimilate more carbon to their body than release of carbon as CO_2 due to their higher biomass. As a result, fungal

Table 8.4 Effect of different management practices on microbial biomass carbon (MBC)

Place	Time (years)	Cropping system	MBC (μg g^{-1})			References
			Conventional practice	Conservation practice	% increase in CA over CP	
India	3	Soybean, wheat	336	385	14.58	Somasundaram et al. (2020)
		Soybean–cotton	299	338	13.04	
		Soybean–fallow	285	297	4.21	
		Soybean–pigeon pea	420	431	2.61	
		Soybean–fallow	296	321	8.44	
		Maize–chickpea	322	408	26.70	
China	7	Maize	171	205	19.88	Zhang et al. (2012)
Mexico	12	Maize–maize Maize–wheat	228	453	98.68	Govaerts et al. (2007)
Mexico	25	Wheat–wheat wheat–sorghum–soybean	290	564	94.48	González-Chávez et al. (2010)

Table 8.5 Alteration in microbial community composition on adoption of conservation practices

Research results	Discussion	References
Clostridia (anaerobic bacteria) were 2.5% more in ZT than CP	ZT and residue application improve SOM, meagre oxidation of OM resulting to increased water storage capacity and high humidity, restricted air exchange, large number of anaerobic microsites are present to support anaerobes	Li and Hung (1987)
30–60% more root colonization of AMF was observed in crops grown under low-input farming than CP	RT decreases the breakdown of hyphae hence imparting stability to fungal populations, retaining more nutrients and providing suppressive effect against pathogenic microorganisms	Goss and de Varennes (2002)
NT along with high C: N ratio containing residues is more potent in supporting MBC and diversity index	Residue with high C:N ratio provides more carbonaceous substrate to microorganisms to build biomass and population thus support high microbial diversity	Garcia and Rice (1994)
Under NT or ZT endophyte or fungi utilizing intact and decaying root dominant while under CT those feeding on fresh residue	Under NT or ZT because of undisturbed environment the rate of residue decomposition is slower, whereas in CP due to intensive ploughing residue breakdown and accelerated rate of mineralization take place	Sharma-Poudyal et al. (2017)
Crop rotation with cereals or fibrous crops supports copiotrophs while legume oligotrophs	Fibrous or cereal crops are having high C:N ratio thus release nutrients slowly, but promote more stable OM as compared to rotation where legumes are used	Sarrantonio and Gallandt (2003)

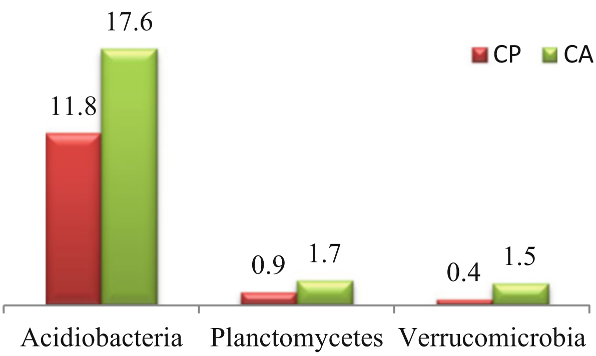

Fig. 8.4 Percentage of microbial community composition under conventional practice (CP) and conservation agriculture (CA)

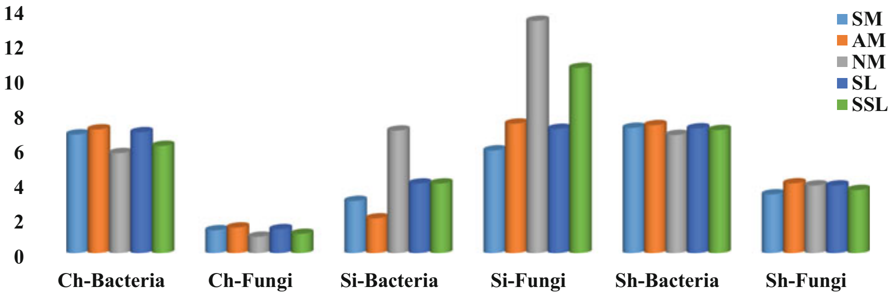

Fig. 8.5 Alteration in diversity indexes along with variation in season and depth of mulching. (Note: As per scale convenience, values of Chao's index have been decreased 10^{-3} times and Simpson's it has increased 10^2 times) (*SM* summer mulching, *AM* autumn mulching, *NM* no mulching, *SL* surface layering, *SSL* sub-surface layering; Adopted from Dong et al. 2017)

communities are predominant under CA. Indexing is a good tool for expressing microbial diversity in soil. Among various indexing parameters, Shannon index (H) and Simpson's index (D) are widely used for diversity analysis. Bacterial and fungal diversity as measured by different indexes is higher under CA as compared to other practices (Table 8.6).

Hierarchical cluster analysis on the basis of carbon source utilization patterns by the microbial communities demonstrates shift in microbial communities under different tillage operations and cropping systems. Microbial community structure under different cropping systems exhibits wide variability where different crops in rotation influence different microbial group with different composition of root exudates.

Ongoing discussion suggests conservation practices together create ecological condition conducive to microbial proliferation of diversified taxa as compared to individual practice in isolation. So, adoption of full set of practices is required for the performance of CA. Above all, the understanding of ecology created by conservation agriculture is essential to draw the benefits from diversity based ecological services for crop production under CA.

8.3 Conservation Agriculture Based Ecology for the Sustenance of Soil Microbial Diversity

8.3.1 Food Security

Food is the prime and basic need of any living entity including soil microorganisms. Abundance of feeding substrate and its quality determine the nature of microbial community in soil. In conservation agriculture, retention of 30% crop residue is mandatory by principle. So, soil is consistently supplied with carbonaceous material as a source of carbon and energy which support vast population of heterotrophic soil microbes under conservation agriculture (CA). Strong supply line hardly creates

Table 8.6 Microbial diversity index under conventional versus conservation practices

Practice followed	Microbe studied	Richness or Chao 1 index (S)	Shannon index (H)/ inverse diversity	Diversity or Simpson's index (D)	References
CT	Bacteria	2448 (5)b	6.52 (0.001) b	5.2×10^3 (0.6×10^{-3})a	Dong et al. (2017)
NT		2635 (7)a	6.69 (0.002) a	3.2×10^{-3}(0.4×10^{-3})b	
PT	Bacteria	–	6.25	0.008	Wang et al. (2016)
CPT			6.15	0.012	
ZT			6.10	0.02	
Tillage (F-value)	Fungi	5.73 (0.02)	1.43 (0.24)	0 (0.98)	Sharma-Poudyal et al. (2017)
CTR-ZTWMb	Fungi (Simpson's index is replaced by evenness study)	91	3.49	0.773	Choudhary et al. (2018a, b, c)
ZT-RWMb		85	3.34	0.751	
ZT-MWMb		95	3.54	0.777	
Farmer's practice	Bacteria (Simpson's index is replaced by PD tree)	8690.763	11.133	249.123	Choudhary et al. (2018a, b, c)
CA based		6898.574	10.507	217.194	

carbon shortage for microbial utilization under CA. Reduced tillage, furthermore, enriches carbon stock by checking loss of carbon being restricted exposed to external forces. Microbial biomass built up by utilizing crop residues is the assured food material for the successive microbial flash. The crop residues retained in conservation agriculture act as a store of nutrients for microbes and plants, prevent leaching of nutrients, increase cation exchange capacity (CEC), provide appropriate ecological condition for biological N_2 fixation (BNF) by microbial utilization of glucose produced by decomposition of cellulose in residues (Gupta et al. 2019, 2020). Conservation practices not only impart food security but also provide nutritional security through balanced nutrition to the microbes and plants through organic and inorganic sources. Crops in rotation including legume as member provide diversified quality feeding substrates to the vast array of rhizosphere microorganisms through rhizo-deposition all through the growing period of crops and support to the growing population in the later part of the growing period by supplying root debris, slough off tissues and dead root mass (Wu et al. 2016). As compared to conventional monoculture, substrate richness under conservation agriculture invites wide array of microbes preferring different substrates.

8.3.2 Habitat Reconstruction

Habitat is the basic need next to food material to the vast population of soil microorganisms for their survival, diversification, proliferation and performance of assigned and accessory duties. Anthropogenic forces in conventional highly intensified agricultural practices demolish habitat by destroying soil structure, creating compaction by heavy vehicle traffic leading to microbial community shift and local extinction of low ecological redundant species in extreme events. Thus, characteristics of habitat are single important consideration for extinction susceptibility of belowground microorganisms resulting in poorly diversified microbial assembles. Tillage, under conservation agriculture by principle is minimum to zero, thus the mechanical force for the destruction of soil structure. Microbial habitat is secured and restored. Moreover, residue retention feeds the soil with organic matter which, in turn, improved soil aggregation protecting microbes in the core of the pore from other external uncontrollable forces. Aggregates create a comfortable and secured microhabitat for residing microbial community that is different from that in the bulk soil (Bach et al. 2018). So crop residue that promotes aggregation, directly or indirectly through earthworm activity is likely to promote soil microbial diversity as well. Gram negative bacteria due to lack of spore formation under stressed condition predominantly congregate in the core of aggregates to avoid external harsh environmental condition. So, diversity of proteobacteria may increase under conservation agriculture. On the other hand, poor aggregation and strong external forces compel spore forming Gram positive Firmicutes to adapt themselves under conventional agriculture. Pore geometry and their relative distribution determine the microbial accommodation capacity in the habitat. Macroaggregates, the predominant aggregate fraction under CA, are oriented itself in different fashions to create more macropores (Gong et al. 2019). Microbes find protected compartment from fungi and bacterivorous nematode and protozoa as well as comfortable zone for their movement and activities which hardly found in conventional intensive ploughed soil resulting in micropore unmatched for many morphologically diversified microorganisms. This phenomenon on the long run leads to habitat loss. Demolished habitat leads to diversity loss of the soil community including keystone species extinction resulting in catastrophic loss in function. This causes reduction in soils capacity to retain its self-perpetuating characteristic.

8.3.3 Microclimate Creation

Conservation practices modify soil microclimate by protecting the soil from the natural destructive forces of rain, wind and sun, improve water infiltration, reduce soil moisture loss and thus regulate the soil microclimate. In case of standing residues (e.g. rice stubble), air temperature at night remains warmer and the air becomes more humid all through the day. This causes a reduction in water evaporation rate from soil and an increase in moisture content within the stubble (Cook et al. 2006) and soil–stubble interface influencing microbial abundance and activities in upper soil profile. On the other hand, flat residues have little impact on the upper layer of soil, rather diurnal temperature ranges are significantly affected by the residue throughout the year. Residues greatly influence on soil temperature after harvest when no-till fields cooled more slowly due to insulation effect of straw having bad conductor of heat transfer. Surface residue decreases the soil water evaporation rate and increases the soil water holding capacity of profile covered with residue. During moisture stress the additional stored soil water is useful for vast communities of rhizosphere microorganisms for their survival under stressful environment.

8.3.4 System Heterogeneity

Biodiversity follows the path of the gradient of environmental heterogeneity (Hart and Reader 2002a, b; Hart et al. 2017). With the increase of system heterogeneity, microbial diversity proliferates. Inherently soils are heterogeneous spatially, more so, with conservation practices. Such practices restore the environmental divergence in terms of aggregation, soil structural integrity, aeration, water, nutrient retention and substrate diversity form leaf litter and rhizo-deposits from robust crop rotation. Aggregates among them create heterogeneity at microscale at which environmental conditions and SOM quality differ from the bulk soil (Hoffland et al. 2020). So, higher microbial diversity is expected under conservation agriculture. On the other hand, intensive tillage, monoculture, water soluble nutrients make the soils under conventional agriculture homogenized. Heavy tillage pulverizes soil aggregates to more uniform microaggregates, incorporates organic matter in soil and uniformly distributes horizontally and vertically which fade the heterogeneity with simplified soil inhabitants. Mono-cropping, on the other hand, reduces substrate richness which, in turn, harbour microbial pools those favour similar type of organic compounds in rhizo-deposits of same crop species in the sequence. Water soluble nutrients from high analysis fertilizers, furthermore, neutralize nutrient gradients and support more copiotrophs with the disappearance of oligotrophs. Thus, diversity declines under conventional agriculture.

8.3.5 Robust Crop Rotation

Package of conservation agricultural practices emphasizes crop diversification, multiple cropping and crop rotation which support different microbial communities by supplying diverse microbial feeding substrates. Such practices not only avoid fallow period but, in addition, minimization of tillage and residue retention, reduce the extent of disturbance against harsh external environment. These make the microbial habitat cosy and secured. Therefore, principles of conservation agriculture are capable of restoring above as well as belowground diversity. Maintaining such diversity is key to success to subsistence of conservation agricultural farmers who

Minimum soil disturbance (under no tillage or reduced tillage).	• Improves soil structure, protect microbial habitat in soil (Lopes et al. 2011). • Re-establishes native microbial genotypes repressed under CT (Peixoto et al. 2006). • Support active decomposer communities (Ogle et al. 2012); promote linkages between rhizosphere and bulk soil networks by maintaining pore connectivity under reduced soil disturbance. • Less disturbance make soil to act as sink by inducing net negative carbon mineralization rather than source under conventional farming (Ashworth 2017). • Destroy macro-aggregates, exposes SOM to atmosphere for rapid oxidation (Six et al. 2000).
Permanent or semi-permanent soil organic cover	• Increase SOC stocks significantly (Liu et al. 2014), Maintain food availability (carbonaceous substrate) to microbes for a prolong especially under cereal crops (maize, oat). • Provide energy source to produce larger microbial biomass (Mangalassery et al. 2015). • Fresh OM at the surface have higher levels of fungi than bacteria as fungi are less sensitive to acidity. • Residue cover act as roof, protect soil, regulate soil moisture and temperature, prevent microbial exposure to harsh environment, cause significant increase in bacterial and fungal count (Dorr de et al. 2012).
Crop Rotation or diversificati on	• Increase above as well as below ground diversity, diversification of diet to microbes to sustain their own diversity. • Include legume in rotation thus improve nutrint status of soil and induce more microbial biomass, microbial diversity and fungal community (Six et al. 2006). • Induce shift in quality, quantity and recalcitrance level of the residue coming from the crop (Sarrantonio and Gallant 2003). • Suitable crop rotations along with conservation tillage allow SOM build-up, sequester carbon thus maintain soil quality and fertility (Corbeels et al. 2006). • Enrich SOC stocks significantly (Liu et al. 2014) and perform as energy source for larger microbial biomass production (Mangalassery et al. 2015).

Fig. 8.6 Practices of conservation agriculture and their effect on soil microbial diversity

are by and large depend on mutualistic and proto-cooperative processes taking place in undisturbed soil (Fig. 8.6).

8.3.6 Carbon Stock and Its Eco-Functionality

Conservation agriculture is basically meant for carbon farming. Reduced tillage, residue retention, crop rotation, cover cropping facilitate carbon addition and its sequestration in soils (Powlson et al. 2016). Soil organic matter has tremendous eco-functional significance in conservation agriculture to make the system microbiologically diversified (Hoffland et al. 2020). Residue retention on soil accumulates cellulose as a component of soil organic matter. Energy rich cellulose sources are eco-functional to promote increased adaptability of decomposers with cellulolytic enzyme system, by which they can gain dominance over decomposers that depend on more simple C-sources (Vivelo and Bhatnagar 2019). Cellulose fuels and shapes the soil microbial community and the environment surrounding those microbes. The downstream product of cellulose hydrolysis is glucose—the energy exchequer for all microbial entity in soil for their survival and functioning. Non-symbiotic nitrogen (N) fixing bacteria may rely on cellulolytic microorganisms for the supply of more available forms of C, and N mineralization is more rapid with a complete web of soil organisms. Such mutualistic interactions are enabled through co-location on or within soil aggregates and pore networks.

8.3.7 System Stability

Ecosystem stability is the prime consideration for restoring secured, cosy and congenial habitat for flourishing microbes and helps the microbes to cope up with stressful events. System stability by and large is the contribution of species richness of soil microbial population (Griffiths and Philippot 2013). In conventional agriculture, intensification of agricultural operational tools and inputs makes the soil environment more chaotic, restless, random and tortuous resulting in higher entropy. Under high entropy, microbes require more energy to perform ecosystem services. They become susceptible to threat due to less energy yielding substrate, particularly, organic matter in soil, in short term and species loss in long term. Thus, microbial pool is less resilient to climatic aberration. Thus, conventional system is thermodynamically unfavourable to soil microbes. In contrary, conservation agriculture as in order due to less external forces employed for agricultural operations yields higher enthalpy. Higher potential energy storage in terms of organic matter stock, diversified rhizo-depositions from varied crop members in rotation create less energy crisis which, in turn, harbour wide array of microbial clads under conservation agriculture. This imparts resistance and resilient to microbes to combat unforeseen biotic and abiotic stresses. Thermodynamically, this system is more stable as compared to conventional one.

8.3.8 Demographic Stochasticity

Increased entropy and chaotic environment under conventional agriculture make the soil microorganisms more competitive for energy acquisition for their growth and development. As a result, there are random fluctuations in population size suppressing one community to others. Such demographic stochasticity has a substantial influence on the growth of microorganisms of ecologically narrow clad and low redundancy and consequently on their extinction risk (Vellend et al. 2014; Shoemaker et al. 2020). Cellulose decomposer, for example, a specialized group of microorganisms called cellulolytic microorganism is conferred with cellulase enzyme to decompose cellulose to glucose—the ultimate source of energy for soil

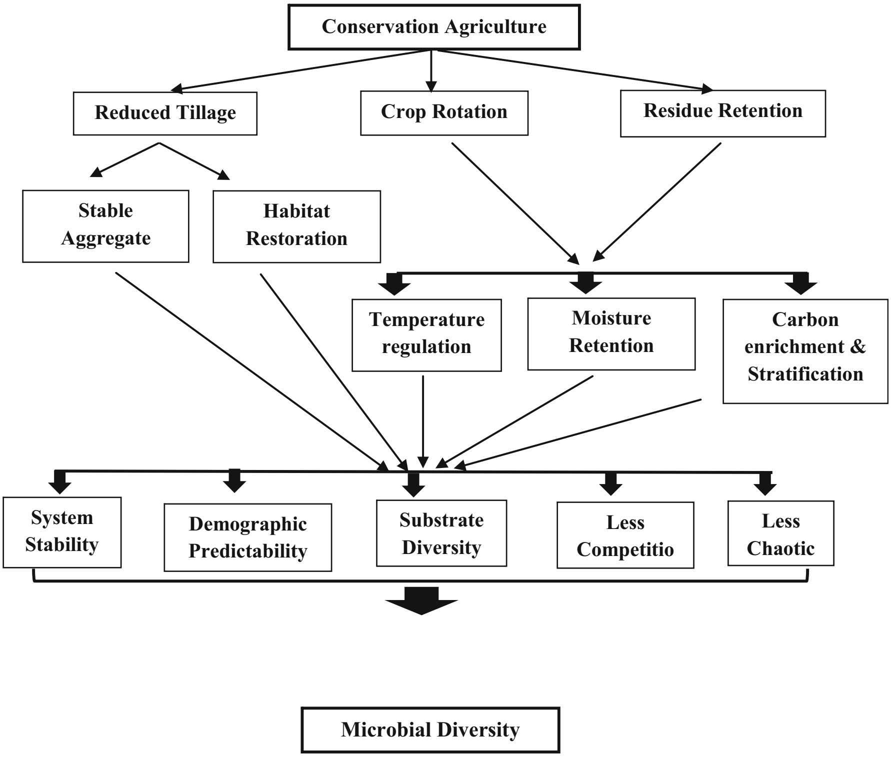

Fig. 8.7 Rejuvenation of microbial diversity through conservation agricultural practices

microbes. Due to demographic stochasticity under conventional agriculture, it results in community shift in short term and species extinction in long-term cases, particularly the fungal cellulose decomposers as compared to bacteria due to higher body size for the former. In contrast, there is demographic predictability due to comparatively stable ecosystem possessed by conservation agriculture. Wide array of microbes is nourished with organic energy sources; flourished abundantly due to less fluctuation in population size. As a result, there is less susceptibility of extinction risk of microbial species under conservation agriculture (Fig. 8.7).

8.3.9 Low-Input Agriculture

Conservation agriculture is a low input-based agriculture where the advantages of soil microbes are explored through proto-cooperation, commensalism and symbiosis by tripartite interaction among soil–microbe–plants (Sarkar et al. 2020). Agriculturally important microorganisms like nitrogen fixing bacteria, phosphate and potash solubilizing and mobilizing organisms, in general, arbuscular mycorrhizal fungi (AMF), in particular, find appropriate ecological condition of low nutrient elements for triggering the expression of respective gene for the synthesis and functioning. Moreover, conservation agriculture supports oligotrophic microorganisms having less competitive among themselves under low nutrient status. Thus, the chance of competitive expulsion and subsequent extinction of species is less. As a result, abundance and diversity of microbial species are restored under conservation agriculture. Copiotrophic microorganisms, on the other hand, are abundant under conventional agricultural soils with high concentration of nutrient elements. They are highly competitive in nature which may result in competitive exclusion of soil taxa with an oligotrophic life-strategy. This phenomenon exerts a constant selection pressure on belowground organisms and consequently causes of species loss at long run. High nutrient concentration, particularly, nitrogen under conventional intensive agriculture compels mutualist to behave as parasite. To assimilate nitrogen, proportionate amount of carbon is required for microorganisms. But, under conventional agriculture due to lack of proportionate carbon, mutualist, particularly, arbuscular mycorrhizal fungi (AMF), draw their required carbon from plant photosynthate parasitically. Such behavioural change has not been attested under low nutrient-based conservation agriculture with ample residue retention on soil as source of carbon to the microorganisms. Oligotrophs have lower growth rates than copiotrophs but they use nutritional resources more efficiently, thus requiring less energy to grow (Che et al. 2020). Therefore, oligotrophic microorganisms could have survived in better physiological conditions or in larger numbers under conservation agriculture than the copiotrophs.

8.4 Importance of Soil Microbial Diversity in Conservation Based Agriculture

Conservation agriculture is a low input-based agriculture. To enhance production-support ecological process and ecosystem service under this practice, the basic principles of low and/or avoidance of unnecessary disturbance, residue retention and diversified crop rotations are framed out. All these principles lead to ecological intensification of CA system where microbes play the pivotal role to extend optimal essential services to the crop plants by their enormous diversity, capacity of having multifaceted functional activities, above all, restoring the system stability to reduce the entropy under abiotic and biotic stresses faced by CA.

It is assumed that increased microbial diversity improves ecosystem services (Maron et al. 2018). The concept though true, CA heavily relies on the diversity of ecosystems service providing specific taxa of microorganisms those have better adaptability under C-rich environment, ecologically low redundant, narrow ecological niche, symbiotic and proto-cooperative mode of interactions, elaborating enzymes system to produce energy yielding molecules by the decomposition of complex residues and having strong defensive mechanisms to control diseases. Diversity of aforesaid microbial groups is susceptible to species losses or shifts in community composition due to inherent threats coming from CA based practices (Table 8.2) and from fluctuation in climatic events. Biodiversity of those specific taxa impacts positive on crop productivity either by ecological enhancement or by ecological replacement as diversity is considered complementary or supplementary to artificial inputs (Kleijn et al. 2019). High biodiversity is essential to enhance the delivery of regulatory and supporting ecosystem services to create win–win situation for agriculture production under CA.

CA is an ecologically intensified production system which is a rich repository of microbial diversity. Such rich biodiversity is essential to maintain ecological processes to support crop productivity even with low nutrient inputs (system stability) and to make the system adaptive to variable nutrients in soil (self-organized). These two properties of CA system arise from the interplay between functionally redundant organisms in the community. Under low nutrient CA system microorganisms with oligotrophic life style come forward in the expense of copiotrophic one and compensate for the loss of function by the more sensitive (copiotrophic) species (Purin and Rillig 2007). Thus, sustainability in productivity under CA may be achieved by making the system stable and self-organized.

Keystone microbes aid to enhance the advantages of plant–fungi interaction for the performance of arbuscular mycorrhizal fungi (AMF) under CA (Hart and Reader 2002a, b). Thus, opportunity of AMF–plant symbiosis should be explored and exploited for the acquisition of limited plant nutrients, maintenance of soil organic matter, improved soil structure, crop adaptation in stressful environment to mitigate the ill effect of salinity, drought, acidity, heat wave, desiccation, toxicity, suppress soil-borne diseases, etc., above all to enhance agricultural sustainability and productivity in the context of CA. As AMF is less palatable to fungivorous fauna, their association with plants and performance is long lasting (Purin and Rillig 2007). The phenomenon is highly desirable to support crop plants for entire growing period under CA. As compared to Gigasporaceae, members of the Glomeraceae are efficient root colonizers and contribute more to nutrient uptake (Hart and Reader 2002a, b). So, AMF communities belonging to Glomeraceae are expected to dominate under CA. AMF belonging to phylum Glomeromycota highly adapted in low-input agricultural systems should be given due attention for taking the advantages of such interaction (Gianinazzi et al. 2010) in CA system.

Nitrification is an essential ecosystem service in low input-based CA system to provide nitrogen nutrition to crops. The process is catered by specialized taxa of a few phylogenetically restricted autotrophic bacteria belonging to *Proteobacteria* (Kowalchuk and Stephen 2001). This group is very sensitive towards soluble organic carbon thus higher concentration soluble carbon in soil (coming from crop residues in CA) declines diversity of nitrifying bacteria. So, maintaining higher nitrifying bacterial diversity is paramount important to run nitrification process either by uniform distribution of residues in field or by placement of residue away from seed rows to reduce soluble carbon concentration. Within nitrifying bacteria, nitrite oxidizing bacteria (NOB) of genus *Nitrosospira* may be dominant one under CA as this bacterium is adapted efficiently at low nitrogen availability with low nitrite oxidizing capacity (Jurburg and Salles 2015). Crops or cropping systems harbouring *Nitrosospira* may be suggested for maintaining higher abundance of *Nitrosospira* under CA. Increased microbial diversity is also an important path to capture reactive nitrogen in microbial biomass (MBN) by internal cycling of nitrogen which otherwise being lost as reactive nitrogen in the environment.

Rhizobia are another important group of service providing bacteria for the acquisition of atmospheric di-nitrogen in collaboration with legumes in low nitrogen status of CA. They are ecologically low redundant belonging to narrow taxonomic group and very sensitive to management (Dogan et al. 2011). Declined nitrogen fixation due to specific rhizobial species loss can hardly be compensated by another member of rhizobium. Species richness and evenness are, thus, deemed important to maintain rhizobial inoculums potential to a level sufficient enough for root infection and formation of nodule for N_2 fixation. Harnessing benefits from diversified non-symbiotic free-living N-fixing bacteria is promising event in CA system. Habitat heterogeneity in ditritusphere, rhizosphere, aggregatusphere, drilosphere and porosphere and fair amount of easily oxidizable C-sources coming from residue decomposition sequestered within the habitats with the restricted oxygen mobility in those habitats make CA system congenial to harbour diversified N-fixing bacteria for efficient nitrogen fixation (Roper and Gupta 2016). Thus, diversified symbiotic and non-symbiotic N-fixing bacteria are to be maintained under CA for making N delivery system sound and synchronous in low N-status soils.

Central path for energy flow in soils under CA is the production of easily oxidizable energy rich glucose molecules from the decomposition of cellulose in crop residues by diversified cellulolytic microorganisms. Successive loading of crop residues under CA greatly reduces soil respiration resulting in accumulation of huge partially decomposed recalcitrant C-moiety leading to retarded C-transformation and sequestration of it into different pools. So, to decompose the cellulosic component of residue for easy seeding by happy seeder and to deliver fuelling molecule to other microorganisms for performing wide array of function, higher diversity of cellulolytic microorganisms is of paramount important. High microbial diversity is expected under CA that can increase the abundance of microorganisms, in general, plant growth promoting rhizo-bacteria, in particular, which suppress soil-borne plant pathogens. The sustainability of CA system relies on service providing communities and their networking. But the values of biodiversity in terms of crop productivity in farm scale are largely an indirect effect that is rarely clear-cut and easily observed.

Box 8.2 Challenges in Harnessing the Benefit from Microbial Diversity Under Conservation Agriculture

Challenges under conservation agricultural (CA) practices	Questions to address such challenges
Proper understanding of soil ecology for supporting microbial diversity under CA	• Do soil organic matter concentrations represent adaptive and optimized endpoints in CA system for supporting specific assemblages of organisms? • How do such endpoints create heterogeneity in soil system to facilitate diverse group of microorganisms across the

(continued)

Box 8.2 (continued)

	gradient of organic matter? • What specific mechanisms account for aggregate formation for stable habitat for the restoration of microorganisms in different level of aggregations? • What specific interactions occur in residue/mulch–soil interface for the creation of microclimate for better microbial ecology? • How sensitive are these mechanisms to spatio-temporal variability?
Limited understanding of the complex response of microbial diversity to conservation farming	• What type of diversity (Genetic, structural and metabolic) is expected under CA? • Is high diversity essential for functioning ecosystem services under low input-based CA farming? • Is ecologically low redundant and mutualistic (symbiotic) microbial diversity essential to explore microbial derived plant benefits under CA?
Identification of keystone microbial species those perform essential services to crops under CA	• What is the diversity of key fungal and bacterial groups that work under low-input agriculture? • Is the diversity of those groups vary with cropping systems and tillage operations or nature of residue? • What specific interactions between plants and microbes enhance nutrient availability to thrive crop plants well under low-input CA system?
Determine management strategies that can be successfully implemented at suitable spatial and temporal scales to promote contributions of microbes to soil nutrient availability	• How do alternative crops suitable for each agro climatic region be adopted for supporting diverse microbial population under conservation agriculture systems? • What approaches can be used to manipulate and manage specific communities for promoting microbes at landscape scales? • What approaches can be used to manage ratios of bacterial to fungal biomass and activity at large spatial scales to maintain plant productivity under low-input CA system? • How can beneficial plant–microbe and microbiome interactions be integrated as promising sustainable solution to improve agricultural production under CA?

8.5 Strategies for Maintaining Microbial Diversity Under Conservation Agriculture

CA by virtue of its goodness retains higher soil microbial diversity and beneficial functions in the low organic matter containing soils than that of the practice following agricultural intensification and crop residue removal. There are, however, few grey areas requiring appropriate interventions for improving soil microbial diversity and their functions for profitable conservation agriculture (Fig. 8.8).

Box 8.3 Constrains, Background and Strategies to Improve Microbial Diversity Under CA

Challenges	Background	Strategies
Herbicide induced soil microbial diversity loss is critical under CA	Conservation tillage is a basic tool to control soil erosion, conserve water and reduce monetary and energy costs, but it can be challenged by inadequate weed control. This leads to heavy reliance on herbicide based weed management, which, in turn, drastically reduces microbial diversity with shift in community structures in CA systems	• Inclusion of crop or crop variety with increasing early crop vigour in the cropping system to suppress the weed growth by competition • Breeding of varieties that produce natural herbicides either as volatile organic compounds (VOCs) or as root exudates containing allelopathic compounds and/or containing early vigour trait • Strategic tillage once in 5–10 years aids efficient weed control under CA system • Strategic placement of nutrients below the seed to escape nutrients being robbed by weeds • Use of biological weed control strategies
Maintenance of signature microbiome for individual management and environment under CA	Microbiome associated with crop roots is as an extended phenotype of plants. It is specific for crop type and cropping system due to rhizosphere effect. It has a major impact on plant growth and development by allocating available nutrients, its health by reducing susceptibility of crop to pathogens and by suppressing soil-borne plant pathogens, in	• Development of designer microbiomes tailored for individual management systems and environments • Plant improvement by engineering of specific gene triggering the synthesis of specific carbon excreted in rhizo-deposition favoured by root microbiomes. (Designer plant–microbe interaction)

(continued)

Box 8.3 (continued)

	general, establishment and survival under stressful environment, in particular	
Enhancing microbial diversity under short-term CA	A time lag between implementation of CA and manifestation of measurable ecosystem service benefits by populations of service providing species is often needed. Such time lag may be several decades for soil services as effects of CA on the genetic diversity of soil microorganisms may take longer to materialize mostly due to perceptible built up of soil organic carbon may take longer period under CA. Uncertainty of system functioning makes the farmers with low economic margin, may reluctant to invest in conservation practices of which they do not know when they will reap the benefits. To ensure farmers desire, diversity of service providing microbes is to be ensured at the early stage of CA adoption	• Selection of cropping system that retains adequate organic matter in soil • Inclusion of arbuscular mycorrhiza (AM) dependent crop members in cropping system • Residue application by manipulating the stoichiometry of carbon inputs (C:N:P:S) • Precision agriculture enabled targeted applications (e.g. to the rhizosphere of the plant) of biological amendments • Global Positioning System (GPS) guided strategic placement of seed in relation to last season's crop rows to capture the rich detritusphere with enhanced microbial diversity and activity compared with inter-row soils • Inoculation of beneficial microorganisms elaborating plant growth, nutrient capture/mobilize disease suppression • Controlled traffic to avoid soil compaction, structural integrity for habitat restoration
Phytotoxicity derived threat to soil biodiversity under CA	Phytotoxicity associated with crop residues is a potential problem facing CA. Successive loading of crop residues under CA greatly reduces soil respiration resulting in accumulation phytotoxins. Proximity of crop residues retained on soil surface may have negative effect on ditritusphere microorganisms.	• Uniform residue spreading to avoid accumulation of phytotoxins detrimental to soil microorganisms • Managing crop residues away from seed rows by developing specially designed mechanical seeder • A booster dose of nitrogen (20–30 kg/ha) in combination with consortia of cellulolytic microbes (*Paecilomyces fusisporus*, *Trichurus spiralis*) and

(continued)

Box 8.3 (continued)

	Decomposition of residues produces water soluble low molecular phenolic compounds detrimental to microorganisms	lignocellulolytic (*Pleurotus sajorcaju*) at 5.0 kg/ha carrier based preparation can be inoculated on leftover residues in properly maintained moist soil • Straw incorporated with cow dung slurry at 5% along with the inoculation of each of *T. harzianum* (cellulolytic) and *P. sajorcaju* (lignolytic) at 5 kg/ha decomposed faster in succeeding crop field • However, in this regard, autochthonous fungi isolated from CA based cropping systems may be used as inoculants for faster degradation of residue in better way to easy doing of zero-till machine to seed in the next crop

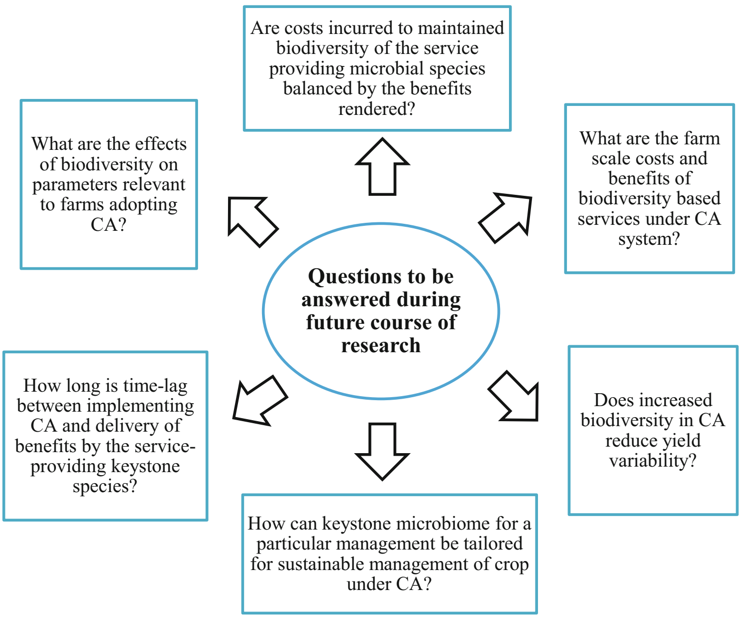

Fig. 8.8 Future scope of research

8.6 Conclusion

Soil microbial diversity as a tool for sustainability in CA system requires a stronger evidence base which is not clear-cut yet and rarely interpreted in the context of crop yield and profits at the farm level. Inventory on microbial diversity under CA has been made widely in the globe and huge information is generated but mostly with very few specific cropping systems and soil types. Research focus on diversity–function relationship to support crop productivity and management cost involved to restore diversity threshold have negligibly been taken to resolve. So, research has to be intensified to make value of microbial diversity-driven ecosystem processes and benefits bagged by the farmers from microbial diversity based ecosystem services. Microbial diversity per se does not have pleasing effect on farmers thus it should be transferred to variables relevant to farmers. More knowledge is needed, particularly on the searching out the keystone microbial species and the effectiveness of those species under CA system over longer periods of time, and in a range of crops, farming systems and different soil types. Keystone species and their functions, thus identified, may be a good marker to the hands of land care managers and researchers for assessing soil health under CA. Furthermore, mass production of keystone microbes for bio-fertilizer production, particularly, for conservation agriculture, will be a new direction in the field of agriculture research. Adaptive research to restore those master microbes under different cropping systems or in tailored cropping systems has to be carried out in farm scale. Evidential results on microbial diversity based performance will encourage the farmers to adopt CA technology in coming future as the prices of external inputs are expected to rise. This will be more beneficial to the farmers of tropic and subtropical countries where agriculture is greatly benefited by internal cycling of nutrients.

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Saline and Sodic Ecosystems in the Changing World

9

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Abstract

Soluble and precipitated electrolytes are the primary cause for developing salinity and sodicity of soil and consequently impede ecosystem functions and limit crop performance. Reclamation of salt-affected soil is a central agenda in current policies of India and salt-affected countries to meet the food-feed-fibre and bioenergy demand of a rising population. Worldwide expansion of irrigated farming in canal commands, sea level rise, shortage of freshwater, coastal land subsidence, erratic behaviour of rainfall, rising in temperature, occurrence of drought demand more evapotranspiration requirement of the plants and consequently import salt-load in the root zone under saline water irrigation or canal commands with improper drainage promote risk of salinization, sodication, high SAR (sodium adsorption ratio), deterioration of soil physical condition, presence of large quality of Mg than Ca, and development of alkalinity in soil. Severely salt affected soil remains near to barren and support very limited plant growth. The low biomass yield and reduced rhizodeposition and crop residue return to soils results in low build-up and storage of soil organic C (SOC) and imbalance in essential nutrients for survival of plant and organism in these ecosystem. Here, we have tried to recount the concept and classification of saline ecosystem, its global extent, and impact of changing climate on salinity and associated stress, effect of poor quality water on salinity development, changes in SOC and nutrients in saline ecosystem. Further, several agro-technological options to mitigating the adverse effect of salinity and need of amendment for rehabilitation of sodic soils are described to combat salinity and sustain crop production.

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Keywords

Salinity · Sodicity · Poor quality water · Climate change · Soil organic C · Nutrients · Amendments

9.1 Introduction

The arable land is finite on this planet. The burgeoning population pressure is a key driver of agricultural intensification. Reclamation of salt-affected soil is a requisite to bring additional land under cultivation to meet the food-feed-fibre and bioenergy demand of a growing population. The reclamation of salt-affected soils is possible options for greening underproductive barren land, secure food for all in the 2030, and meet the agenda of 'Sustainable Development' (Sustainable Development Goal 2017). Saline and sodic ecosystem limit crop growth, performance, and yield as soil and water of these systems are largely affected by the presence of different electrolytes of varying degree of solubility and precipitation. Generally salts are geo-genic in origin and present in soil and water or both in arid and semiarid ecologies. Further, long history of irrigation with saline, wastewater and poor quality water and impeded drainage conditions also aggravate soil degradation. Currently, expansion of irrigated farming in canal commands and perceived climate changes, particularly increase in temperature, erratic behaviour of rainfall will raise evapo-transpiration (ET) requirement of the plants and consequently import salt-load in the root zone under saline water irrigation or canal commands area having improper drainage. Mediterranean coast becomes desertified by increasing soil salinity (Daliakopoulos et al. 2016). Therefore, monitoring the soil and water salinity and its degree of severity is imperative to quantify harmful effect on crop productivity and environmental degradation. Salt-affected soil (SAS) classified as: saline soil contains appreciable amount of soluble salts [soils generally have electrolytic conductivity of the soil water saturated paste extract (EC_e) more than 4.0 dS m^{-1}at 25 °C, pH of saturation paste (pH_s) <8.2, and exchangeable sodium percentage (ESP) <15 (Abrol et al. 1979)] that may be neutral in reaction and/or endow with a saline water table in soil strata. The upward flux of underground saline water in root zone, long-term irrigation with saline/waste water and impeded drainage or intrusion of saline or brackish water can provisionally develop salinity in sea coast area (Singh 1998; Soni et al. 2021; Mitran et al. 2016); sodic soil: small concentration of electrolytes are present in sodic soil but carry significant amount of carbonated salts in soil and presence of Na^+ in exchange phase of soil clay and silt having potentiality to give alkaline reaction upon water hydrolysis (soils have an ESP of more than 15, $pH_s > 8.2$, and variable EC_e). Sometime soil may became provisionally sodic with prolong irrigation with sodic water (alkaline in reaction) (Minhas et al. 2019); saline–sodic soil: as the EC_e of some sodic soil are variable, a groups of soils having pH_s >8.5, ESP >15%, SAR >13, and EC_e >4 dS m^{-1} at 25 °C are defined as 'saline–sodic'. These categories of soils develop because of applying irrigation waters containing high residual sodium carbonate (RSC > 2.5 me L^{-1}), and soils with shallow sodic water table.

9.2 Global Extent of Saline Ecosystem

Nearly 20% of cultivated land has been less productive and extreme case with conjoint problem of waterlogging and salinization. The shallow saline water table in root zone ultimately transforms the affected land to wetland desert. The limited availability of freshwater, salinization, and erosion create a complex problem in rain fed area. Over 1100 mha of Global land area is affected by salt-affected soils and related problems to varying extent. Salinization is a severe problem in middle East (189 mha), Australia (169 mha) and North Africa (144 mha), Europe (30.7 mha) and 52 mha area of south Asia (Sharma 2017). Around 120 mha land of India is affected with degradation. Among them soil erosion and acidity are two major problems besides other problems like excess salts, nutrient toxicities, and waterlogging. In India total salt-affected lands cover 6.74 mha; among them sodicity occupies 3.79 mha and salinity contributes 2.95 mha of salt-affected area. These lands cover ten states of country; among them five states, i.e. Gujarat, Uttar Pradesh, Maharashtra, West Bengal, and Rajasthan together share 75% of the total SAS. In India currently salinity diminishes ~5.66 million tonnes of produce valued at Rs 8000 crores and sodicity causes annual loss of ~11 mt (Rs 15,000.0 crores) (Sharma et al. 2015).

9.3 Salt-Affected Soil in Changing Climate

Abnormal rainfall creating the phenomenon of drought, climate change, sea level rise, irrigation water shortage and coastal land subsidence, groundwater overexploitation, more irrigation water requirements, increase of floods and flash floods, adversely affected the living component of ecosystem. The increase in mean annual temperature and warmer winter and increase in night temperature trigger the incidence of drought (Bhardwaj and Srivastava 2013). The frequent occurrence of drought and prolong water stress increase the evapotranspiration demand and aridity and bring the problem of salinity especially in shallow water table areas. Salts along with capillary water travel to the overlying rhizosphere. The water availability for plant is influenced by various soil properties, field capacity, plant available water content, soil texture, and nature and quantity of salts present. The increment in salt content in soil profile and higher salt concentration in soil solution alter the osmotic potential of water affecting its availability to plants. The projected climate change and associated change in salt-affected soils are described in Table 9.1. Along with this, high temperature raises the drier conditions which increase water stress and accentuate demand for water. Salt-affected soils with the alkaline pH and presence of electrolytes in soil solution and sodium saturation of exchange complex (sodic/ saline–sodic soil) adversely affect soil biota and plant biomass and ultimately crop yield. Climate change may further aggravate the salinity and sodicity effect in soil. In 11 countries, about 29.6 mha of total 158.7 mha irrigated area is affected with high salt content (Dregne et al. 1991). Increasing salinization of natural resources like soil and water is now regarded as degradation of environmental quality. Rises in water

Table 9.1 Climate induced projected change in salt-affected soils: implication and threat

Regions	Projected driving change	Resulting threat
Australia	Risk of sodicity	Multiple constraints such as alkalinity, sodicity, and irrigation induce salinity and marginal quality irrigation (Rengasamy 2006)
Argentina	Threat to develop sodicity	RSC irrigated in rice grown Vertisols (Sione et al. 2017)
Iran, Iraq, and Central Asia	Calcareous saline–sodic soil, groundwater contain salinity, excess Mg than Ca	Salinity and sodicity stress, groundwater contain soluble salts, Na^{+}, Mg^{2+}, carbonate and bicarbonate ions (Raiesi and Kabiri 2016)
Central and eastern Europe	Slow groundwater recharge	Soil salinization in marginal areas (Falloon and Betts 2010)
Pan Europe	Increase risk of flood hazard	Salinization due to increased water loss past crop root zone (Daliakopoulos et al. 2016)
Indo-Gangetic plain, India and Pakistan	Risk of sodification and salinization	Sodification due to inherent soil of aeolian deposit, area irrigated with saline/sodic water irrigation, canal command area irrigation induce salinity (Choudhary et al. 2011; Murtaza et al. 2008; Sheoran et al. 2021)
Indo-Gangetic plain	Sodicity and rainfall aberration	Waterlogging and elemental toxicity of Al, B, Fe and Mn for wheat in winter (Sharma et al. 2018; Kulshreshtha et al. 2020)
India Deccan Plateau	Risk of sodification, deterioration of soil physical condition	Problem of impaired drainage, waterlogging (low saturated hydraulic conductivity), and adverse soil physical conditions but without evidence of salt-effloresces, groundwater contain variable electrolytes, besides salinity, presence of large quality of Mg than Ca, high SAR, and appearance of residual CO_3^{2-} and HCO_3^{2-}(Vaidya and Pal 2002; Shirale et al. 2018)
Coastal Sundarban, India and Bangladesh	Risk of saline/brackish water intrusion and inundation with tidal water from sea level rise, damaging wetlands; heightened storm threat	Shallow water table rich with soluble salt, lack of proper drainage, heavy rain at *Kharif* season and lack of good quality irrigation water at *rabi* season, losses from heightened storm surges pose the greatest threat to agriculture, aquaculture, infrastructure, livelihoods, and public health (Dasgupta et al. 2015; Mandal et al. 2019; Mitran et al. 2014)

table and mobilization of salt create other problems and inhibit the growth thus affect the productivity. Further, poor soil physical condition, viz., impeded hydraulic conductivity, low infiltration, poor aeration, is major constraint for crop production. Climate plays a crucial role in maintaining the soil properties. Increment in sodicity accelerates the problem of clay dispersion, slaking and breakdown the soil aggregates and loses the physical protection of soil organic matter from decomposition.

9.4 Poor Quality Water: An Ever Increasing Threat

Salinization of the good quality surface and groundwater resources are growing water quality challenge that impedes food security, sectoral water use, biodiversity conservation, and ecosystem services (Cañedo-Argüelles et al. 2016; Thorslund and van Vliet 2020). South Asia has only ~4.5% of global annual renewable water resources to support the livelihoods of 25% of the earth population. Ironically, 90% of the available water is utilized for irrigation in South Asia. India shares 2.5% of earth area and contains 4% of water resources and supports ~16% of world population. In India, 60% of irrigation needs are met with groundwater wells. Unsustainable water use for irrigation cause rapid decline in water table as well as irrigation led salinity in many places. Arsenic and fluoride contamination of groundwater is noticeably increased (Sarkar et al. 2012). In trans-Gangetic plains of India, huge gap of 1000 mm water requirement between the available (~800 mm; canal: 200 mm) and actual water requirement (1800 mm) of rice–wheat cropping system (RWCS) leads to bound saline groundwater in irrigation. Salinity and alkalinity are the key hazard associated with saline, sodic and RSC water irrigation (Minhas et al. 2019; Sheoran et al. 2021). A category of SAS affected with large deposition of soluble salts that may be neutral in reaction and/or endow with saline water table; others carrying less deposited salts but have a potentiality to give alkalinity upon water hydrolysis. Sometime prolong irrigation with sodic water (alkaline in reaction) can have provisional occurrence of sodic soil (Choudhary et al. 2011; Minhas et al. 2007; Sundha et al. 2020). *Vertisols* in central and southern India under semiarid climatic condition with moderate rainfall (annual rain ~875 mm) favour to develop calcareous sodic soils. The Purna Valley of Maharashtra state often shows the problem of impaired drainage, waterlogging (low saturated hydraulic conductivity), and adverse soil physical conditions but without evidence of salt-effloresces (Vaidya and Pal 2002; Bhattacharyya et al. 2018; Shirale et al. 2018). The water quality used for irrigation is the key issues for deterioration of soil physical condition. Presence of large quality of Mg^{2+} than Ca^{2+}, high SAR and appearance of residual CO_3^{2-} and HCO_3^{2-} degrade soil physical condition (Balpande et al. 1996; Vaidya and Pal 2002; Qadir et al. 2018; Bogart et al. 2019). Presence of fine montmorillonite minerals rapidly declines the soil hydraulic conductivity (Ks) in Vertisols. An increment in Mg to Ca ratio >1 in irrigation waters and exceeding exchangeable magnesium percentage (EMP) > 25% in soils are an indicator for soil degradation and deleterious impact on environmental quality (Basak et al. 2015a). Therefore, external supply of Ca and disposal of Mg salts are advocated to mitigate this adverse effect (Qadir et al. 2018).

9.5 Soil Organic Matter in Saline/Sodic Environment

Soil organic C plays a centric role in maintaining soil quality as it restores soil structure, fertility, nutrient cycling and regulates microbial activity. The roles of soil organic matter will vary according to SOM pools. Soil pH, nature, and quantity of available electrolytes and their speciation have paramount influence on dissolved organic carbon (DOM) and other readily mineralizable pool (Setia et al. 2014). Smith et al. (2009) estimated that the agricultural soil will lose up to 62–164 Tg C by 2100. Sodic soil with high amount of Na in exchange sites affects plant growth and climate change may aggravate the problem. The less biomass yield and reduced return of rhizodeposition and crop residue show low build-up of soil organic C in these soils (Bhardwaj et al. 2019; Datta et al. 2019; Wong et al. 2010). pH dependent charged fractions of SOM contribute to anion or cation exchange reaction. The presence of HCO_3^- and CO_3^{2-} increases the dissolution of DOM by two to four fold when soil pH >8.0 (Yin et al. 1996). DOM is prone to water erosion and rapidly decomposes in strongly alkaline environment. The external addition of DOM increases the sorption of dissolved organic C. With preponderance of CO_3^{2-} concentrations DOC content is increased, the amount of adsorbed DOC decreased significantly in comparison to the addition of SO_4^{2-} and Cl^-, when basic cations are maintained in similar proportion (Tavakkoli et al. 2015). The amount of sorbed C in saline soil is explained by the covalency index and zeta potential of cation. Among the basic cations the Ca^{2+} followed by Mg^{2+}, K^+, and Na^+ showed the increment in zeta potential and the decrement in covalency index (Setia et al. 2014). Oppositely, ionic bond readily broken by water solvation when monovalent basic cation takes part for SOM sorption. The overall salinity stress is dynamic; therefore, fluctuation in salinity affects decomposition of rhizodeposition and presence of DOC in rhizosphere. Salt-affected soil carries lower amount of organic C (Table 9.2). Therefore, the increment in salinity, moisture stress along with temperature rise further declines DOC in salt-affected soil (Liu et al. 2017; Datta et al. 2019). In such cases organic mulching favours microbial growth and utilizes organic substances and resides lower amount of DOC in mobile form (Mamilov et al. 2004; Mavi et al. 2012).

9.6 Plant Nutrition in Salt-Affected Soil

Presence of excess of electrolytes in soil water environment during crop establishment leads to salinity build-up. These cause imbalance or deficiency/toxicity of essential element and reduced the survival of microorganism due to desiccating soil environment and resulted in shift in microbial community with reduced efficiency of substrate utilization (Ghollarata and Raiesi 2007). Soil reaction depends on solubility, complexation, precipitation-dissolution, speciation of electrolytes those are

Table 9.2 Walkley-Black organic C concentration (WBC) in different categories of salt-affected soils (at 0–15 cm depth)

Category	pH_2	EC_2 (dS m^{-1})	WBC (g kg^{-1})	Reference
Saline	7.6 (pH_s)	5.5 (EC_e)	2.9	Basak et al. 2015a
	7.3 (pH_s)	13.3 (EC_e)	11.0	Basak et al. 2015a
	8.2 (pH_s)	16.2 (EC_e)	4.6	Soni et al. 2021
Sodic	8.5–10.4	<1.5	1.8–4.0	Bhardwaj et al. 2019
	8.8	0.8 (EC_e)	2.0	Basak et al. 2015b
	9.2	0.54	2.1	Singh et al. 2014
	10.6	0.89	0.8	Mishra et al. 2014
	9.8	1.9 (EC_e)	0.3	Nayak et al. 2013
	9.1		2.1	Yaduvanshi and Sharma 2008
	9.1 (pH_s)	0.9 (EC_e)	2.5	Basak et al. 2016
Saline–sodic	10.2 (pH_s)	12.2 (EC_e)	1.1	Sundha et al. 2020
	9.1	45.0	2.7	Basak et al. 2015b
Reclaim sodic	8.4	0.2	2.8	Gupta Choudhury et al. 2018
	8.6[a]	0.9[a]	2.4[a]	Nayak et al. 2013

[a]The improvement of soil properties after three of Rice–wheat cropping with 50GR mineral gypsum (eq. 10.5 Mg ha^{-1}) application before the onset of first year rice

moderated by soil pH. Nutrient uptake and root development of plants depend on soil pH and interactions among soil particles in aqueous soil medium (Rengasamy 2016). The distribution of nutrients in soil is allocated into pools of total concentrations, exchangeable, bound to ligands, complexed with conditional stability constants, plant available forms, and expressed as mass balance of each electrolytes. Adoption of management practices (easily decomposable organic substrate, well mature compost, reduced and/or zero tillage and mulch) favoured the N mineralization rates due to intensification of soil microbial activity and supports the aboveground and belowground biomass (Mitran et al. 2017; Yan and Marschner 2012; Soni et al. 2021). Soil P dynamics are affected due to changes of P sorbent sites in soil because of supply of Na^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Dominguez et al. 2001; Meena et al. 2018; Sundha et al. 2017). Addition of organic mulch reduced fixation of water-soluble P due to presence of ligands substances and facilitated mineralization of organic P (Wang et al. 2011).

9.7 Technological Options for Salinity Management

From the beginning of establishment of ICAR-CSSRI, Karnal developed remedial measures for enhancing agricultural production in salt-affected areas of the Country. Undertaking a pan India mandate, the immediate focus was on reclaiming the sodic land of Punjab and Haryana states therefore it could be beneficial for that area and improving livelihood of community of that area. Successful field and laboratory

Table 9.3 Effect of mulching and consumptive use of saline water on reduction of soil salinity (dS m^{-1}) (Basak et al. 2017); numbers followed by different uppercase letters (a–c) significantly different at $P \leq 0.05$ by Duncan multiple range tests for separation of mean

Treatment	EC_e (dS m^{-1})
Uncultivated fallow	10.0^{a}
100% best available water	4.25^{c}
100% water requirement with 8.0 dS m^{-1}	7.7^{abc}
100% water requirement with 8.0 dS m^{-1}-mulch 5 t ha^{-1}	8.8^{ab}
60% water requirement with 8.0 dS m^{-1}	5.7^{bc}
60% water requirement with 8.0 dS m^{-1}-mulch 5 t ha^{-1}	9.6^{a}

experiments standardized the existing technology for specific locations. Irrigation followed by drainage with seasonal rain, canal, or underground fresh water are the feasible option to remove excess salts and electrolytes in soils (Rao and Visvanatha 1998). The leaching of salts from the soils depend on the quality and quantity of irrigation water and texture of soils. Gypsum application or irrigation with low SAR water is favoured for improvement in soil physical structure and desirable leaching (Rai et al. 2014). Sometime flushing with water is applicable to remove surface deposited salts. This procedure is advocated in low permeable soil and soils are susceptible to hard crust formation. Scraping of deposited salts is prescribed to manage small land holding affected with salinity; however, a frequent removal of salts is required to achieve desired and productive plant growth and crop production (Chhabra 1996). Field scale salinity management needs proper soil, water, and crop management strategies to sustain cultivation in saline soil and mitigation of increasing risk of soil salinization and sustaining soil and environment quality. Properly levelled crop field, conservation tillage (minimum tillage), mulching, conjunctive use of saline water, cycling and mixing mode of irrigation, frequent application of saline irrigation for reduction of salt accumulation in root zone (Table 9.3), irrigate with best available water at germination and seedling emerging stages, pre sowing irrigation for *kharif* crop, and improving water use efficiency practice by pressurized sprinkler irrigation facilitate in reducing root zone salinity and sustaining crop production in salt-affected lands and use of saline water (Minhas 1998; Rai et al. 2017). Application of mulch prevents crust formation, conserve soil moiture for the longer period and improves soil biological actvity.

Different categories of saline soils are rehabilitated with specific management options:

9.7.1 Inland Saline Soil with Shallow Water Table with Poor Quality Water

Sub-surface or surface drainage is a long-term solution for lowering water table and leaching of salts and to provide a favourable salt-balance in root zone (Rao and Visvanatha 1998). Perforated corrugated PVC pipe covered with synthetic filter mechanically installed in proper plan below the rhizosphere depth to lower down poor quality water table and leach excess salt and water (Chinchmalatpure et al. 2015). Bio-physical characteristics of salt-affected area like soil texture, geology, hydrology, rainfall, potential evapotranspiration, growing degree day (GDD), concentration and nature of salt present, and predominant cropping systems are the factors to determine the spacing and depth of drainage lines. Several countries like the USA, Egypt, and Gulf countries use this technology to manage a sizeable area of saline soil. In India, ~40,000 ha waterlogged saline areas have been reclaimed using this technology (Chinchmalatpure et al. 2015). Appreciable yield is achieved in fields having a sub-surface drainage system than in fields with a deep water table and the differences were larger at applied water salinities of more than 10 dS m^{-1} as horizontal sub-surface drainage improves aeration in the rhizosphere by lowering water table and reducing salts concentration. Around INR 0.6 and 0.75 lakh is the implementation cost for this technology for managing salinity in alluvial Gangetic saline land and heavy texture *Vertisols* of southern states, respectively.

9.7.2 Costal and Deltaic Saline Soil

Preventing the ingress of brackish saline water and seawater tides is possible by constructing high and well designed earthen dykes, and these embankments prevent the back flow of this water into rivers and estuaries. Construction of pond and water harvesting structures to capture monsoon rain and future use for irrigating *rabi* crop and leaching of salts (Chinchmalatpure et al. 2015). 'Land shaping techniques' is an advance practice of modifying land surface by developing raised and sunken bed by alternately digging soil from one strip and putting it on the other. This minimizes the capillary rise to avoid salt deposition in root zone (Mandal et al. 2019). For ease in using available farm machinery, minimum width of raised bed is taken as 2.0 m and the height of sunken bed is 1.0 m above ground surface. The average depth of sunken bed is 0.5 m below ground surface and side slope is 1:1. Vegetables and forages are grown in raised and deep water paddy in sunken beds.

9.7.3 Bio-Drainage

Physiological transpiration of tree is used to remove excess soil water to manage shallow water table. It is an effective option to prevent the development of waterlogged and saline soils with problem of drainage congestion (Dagar et al. 2016). This eco-friendly low cost technology is easily adopted by farmers with additional benefit of wood biomass and promotion of social forestry. This technology is recommended to manage seepage from higher elevation, surface discharge of habitation and industrial waste or flood water management in canal command. It minimize the accumulation of salts in the root zone rather than remove salts.

9.7.4 Technological Options for Sodicity Management

Gypsum, pyrites, aluminium chloride, inorganic sulphur, etc., were initiated for reclamation of sodic/saline–sodic soils (Sharma and Swarup 1997; CSSRI 2006). Based on the source, and potentiality to neutralize sodicity, amendments are broadly categorized into: inorganic/chemical and organic agents. Chemical amendments for sodic soil reclamation can be broadly grouped into three categories: (a) soluble calcium salts, e.g. calcium sulphate (mineral gypsum/processed $CaSO_4.2H_2O$ in industrial plants in chemical reaction, calcium chloride); and (b) acids or acid forming substances, e.g. sulphuric acid, iron sulphate, aluminium sulphate, lime sulphur, sulphur, pyrite, etc. Besides, organic sources such as farmyard manure, corn stalks (Li and Keren 2009), municipal solid waste compost (Sundha et al. 2020; Singh et al. 2017), sewage sludge, pressmud (Sheoran et al. 2021), crop residue (Choudhary et al. 2011) are being used as alternate amendment sources. In addition soil organic matter improves soil structure and aggregation, increases hydraulic conductivity, and promotes higher nutrient levels and increases cation exchange capacity (Jalali and Ranjbar 2009).

Besides mineral gypsum, seawater and some chemical plants are sources of by-product marine gypsum and by-product chemical gypsum, respectively. The latter is obtained as by-product phospho-gypsum or fluoro-gypsum or boro-gypsum, FGD (flue gas desulfurization) gypsum, depending upon the source. Fluoro-gypsum obtained as by-product during the manufacture of aluminium fluoride and hydrofluoric acid using fluorite at different units in Surat, Mumbai, and Thane. Another by-product, boro-gypsum is obtained at the plant which refines calcium borates (colemanite and ulexite) to produce borax and boric acid manufactured in districts of Maharashtra and Chennai. Fluoro-gypsum and boro-gypsum are not used as amendment sources but other forms such as marine gypsum, phospho-gypsum, and flue gas desulfurization gypsum are being researched for agricultural usage in different parts of the world (Table 9.4).

9.8 Conclusions and Way Forward

Salts are the integral part in salt-affected soils and irrigated agriculture. Salt-affected soils are classified as saline, sodic, and saline–sodic on the basis of salt presence. Suitable remediation is advocated for reclamation of saline and sodic or saline–sodic soil. The salinity and sodicity reclamation is a prerequisite for maintaining soil quality of salt-affected soils. Devising agronomic practices which mitigate the impact of predicted climate change, promotion of conservation agricultural practices (such as zero tillage, bed planting, residue management, inclusion of legume, crop rotation). Screening, identification of genes for tolerance to moisture, heat, cold, and abiotic stress and improve the use efficiency of water, nutrients, energy, and agronomic inputs. Promote crop insurance, multi enterprise agriculture, early warning systems to reduce the impact of weather aberrations due to climate change. Reclaimed soils are productive and proper management can brings great

Table 9.4 Commonly used amendment for reclamation of sodic soil

Amendments	Nature and mechanism to neutralize soil sodicity
Gypsum ($CaSO_4 . 2H_2O$)	Sparingly soluble in water and widespread in nature as soil component and advantages with gypsum is relatively faster reclamation Na-Clay-Na + $CaSO_4 \rightarrow$ Ca-Clay + Na_2SO_4
Ground limestone ($CaCO_3$)	Supply Ca on dissolution
Agro-industrial wastes (pressmud)	Mobilizing inherent calcite (Sheoran et al. 2021)
Sulphuric acid (H_2SO_4)	Dilute acid use as sodicity reclamation amendments
Pyrite (FeS_2); Iron sulphate ($FeSO_4$, $7H_2O$); Elemental Sulphur (S); Lime Sulphur (CaS_5)	Acids forming amendments; The oxidation of elemental S/pyrite is mediated by *Thiobacillus thiooxidans,* which requires a warm, well aerated, and moist soil with low pH condition. $2S + 3O_2 = 2SO_3$ (microbiological oxidation) $SO_3 + H_2O = H_2SO_4$ $NaHCO_3 + H_2SO_4 = Na_2SO_4$ (Leachable) + $H_2O + CO_2$ $Na_2CO_3 + H_2SO_4 = Na_2SO_4$ (Leachable) + $H_2O + CO_2$ Na^+-[Soil]-Na^+ + H_2SO_4 = H^+-[Soil]-H^+ + Na_2SO_4 (Leachable)
Farmyard manure (FYM) and green manuring (GM)	Organic acids released from organic amendments mobilize Ca from inherent and precipitated $CaCO_3$ in calcareous soils and consumption of mineral gypsum decline for sodicity reclamation in sodic water irrigation for achieving sustainable yields
Compost	Gypsum (GR25) and 20 Mg ha^{-1} city compost are recommended for reducing alkalinity and salinity stress of soil under use of poor quality water (Sundha et al. 2020)
Flue gas desulfurization (FGD) gypsum: Synthetic gypsum produced as a by-product of industrial processes	FGD gypsum having small particle size facilitate the reaction between gypsum and sodic soil. The corn emergence ratio and yield in FGD amended soil was 1.1–7.6 and 1.1–13.9 times than control. FGD improved aggregation, declined pH and ESP in saline–sodic soils (Zhao et al. 2020)

opportunities to increase food security, livelihood security, in developing countries. Reclamation and management of salt-affected area can increase primary productivity and help in sequestration of C and to meet climate change mitigation goal. Soil pH and presence of electrolytes maintain nutrient availability and soil C dynamics. The inherent and canal command irrigation network area require regular assessment and monitoring for planning agricultural practices to achieve good yield and strengthening livelihood of salt-affected region.

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10 Approaches in Advanced Soil Elemental Extractability: Catapulting Future Soil–Plant Nutrition Research

Shubhadip Dasgupta, Sudip Sengupta, Sushanta Saha, Abhijit Sarkar, and Krishna Chaitanya Anantha

Abstract

The green revolution has driven the world to a concept of food sufficiency, but its aftermath in the form of injudicious chemical application has robbed off the inherent productive capacity of the soils. A large number of nutrient deficiencies are cropping up day by day severely impeding global nutritional security. The current situation emphasizes the vehement need for soil fertility status investigation. Although the researches for individual soil elements using diverse chemical extractants are in vogue for several decades, it faces the major hindrance in terms of cumbersome protocols and humongous labour and time consumption. This results in a substantial delay in the soil testing services and the farmers do not get correct information on the soil fertility status before crop cultivations aggravating the low productivity conundrum. A paradigm shift in the soil elemental extractability research is thus gaining significance steadily. The use of multinutrient soil chemical extractants aims at pulling out a large number of elements at one go into the solution, and thereafter its instrumental characterization is emerging as a potent replacement. It can save quite a lot of time and labour involvement and propel the fertility evaluation process in soil and plant nutrition studies. Accentuated by the advances in the field of instrumental elemental

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characterization with the involvement of atomic absorption spectrometry (AAS), microwave plasma-atomic emission spectrometry (MP-AES), inductively coupled plasma-optical emission spectrometry (ICP-OES), inductively coupled plasma-mass spectrometry (ICP-MS), ion selective electrodes (for anions), etc. the research is promulgating by leaps and bounds. The ability to extract and detect even the toxic metal constituents of the soil at a single extraction and using the high precision instruments is an additional benefit of the research. This chapter underscores the effort to impart due cognizance to the advanced research protocols of soil elemental extractability to catapult the future of soil–plant nutrition research astutely.

Keywords

Soil · Plant nutrition · Elemental extraction · Multinutrient extractants · Advanced instrumentations · Critical soil nutrient concentration · Soil testing

10.1 Introduction

Post-Green Revolution to the present day has been a story of agricultural development through transformations regarding subsistence farming to sustainable farming and deficiency in food grain production to its sufficiency (Sengupta and Dey 2019). The global distribution of the essential plant growth-promoting nutrient elements, especially nitrogen (N), phosphorus (P), and potassium (K) is quite diverse from region to region as well as in plant surroundings (Rashid et al. 2016; Zhang et al. 2018). This situation culminates in full-scale applications of chemical fertilizers to boost soil fertility and sustain better agricultural produce (Singh Brar et al. 2015). However in reality to augment the production hitherto, there has been a continuous increase in fertilizer use and consumption, while, conversely, this indiscriminate application culminated into several nutrient deficiencies occurring in soil (Ma et al. 2020). The injudicious application of several NPK fertilizers, especially urea, had skewed the fertilizer consumption ratio, which upon its interactions with other nutrients has doomed their availability and progress of the agricultural sector as a whole (Bhattacharya et al. 2019).

Soil serves as the reservoir of innumerable elements of which about 20 elements are essential for the sustenance of plants in one way or the other. Optimizing the levels of essential elements like nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), boron (B), molybdenum (Mo), nickel (Ni), and chloride (Cl) as well as non-essential but beneficial elements like vanadium (V), silicon (Si), selenium (Se), and cobalt (Co) seems the viable option for agricultural sustainability (Dimkpa et al. 2017). In this multitude of nutrient requirement of the crops, different fertilizer formulations have evolved and tested on the soil in terms of crop response with a response varied from 10 to 100% (Dimkpa and Bindraban 2016). It is this excess level of nutrient not availed by the plant that culminates into disproportionate nutrient availability and environmental pollution issues. On the contrary, use of organics alone is not enough to supply plant nutrient for optimum yield (Dasgupta et al. 2017). Thus the fertilizer combinations need to supply bioavailable nutrients for plant tissue uptake at critical levels to render their application valid.

The situation above has necessitated a thorough evaluation of the deficiency, sufficiency criteria of different nutrients in the soil. The most logical strategy for scheduling fertilizer recommendation, till date, operates through soil test based crop correlation models. The established and accepted method for soil testing, so far, involves single element extraction and determination at a time. This involves exorbitant time, workforce, and cost and globally, alternatives are rigorously sought. The research for viable alternatives brings forward the issue of multinutrient extractants which provides the option of extracting and assaying more than one nutrient in one go (Bibiso et al. 2015).

To usher a globally acclaimed soil testing and fertilizer recommendation protocol, the research interest in 'universal extractants' is on the rise (Sims 1989). The practicability of a possible multinutrient universal extractant is coined and envisaged as an advantage to third world countries, as they often face the crunch of hard currency, chemicals, precise instruments, and workforce in the laboratories (Mamo et al. 1996). The process involves the extraction and use of multi-element analysers such as the ICP-MS, ICP-OES, etc. based upon absorption and emission spectrometry principles and possessing automated flow injection analysers for soil extract assay (Rakshit et al. 2020). All in one they seem to assess soil nutrient status in a cost-effective, time, and labour saving way through single step assay (Pradhan et al. 2015; Seth et al. 2018) and thus enable availing vital plant nutrition response data to the farming communities in a short period of time and thus promulgate agricultural sustainability.

In this purview, we have tried to inculcate the idea of the paradigm shift in the field of soil testing and plant nutrition through modern concepts of extracting nutrient and instrumental facilities in a wholesome, holistic manner to catapult the future soil science research.

10.2 Addressing the Issue of Soil–Plant Nutrition Relationship Studies

10.2.1 Dynamics of Soil–Plant Nutrients for Agricultural Sustainability

The soil is a repository of a diverse group of elements each exhibiting their properties in their active and benign state. From the agricultural sustainability and food productivity points of view, it is the bioavailable portion of these elemental constituents that deserve particular emphasis. The co-occurrence of different abiotic and biotic factors can often serve as hindrances in the availability of the nutrients for plant growth. Therefore a priori knowledge of the dynamics of the nutrient elements in the soil, their bioavailability edaphic interferences is of paramount importance and encompasses critical ex situ chemical extraction and analysis protocol to mimic plant uptake (Dimkpa et al. 2017). A schematic representation of the relationship of soil–plant nutrition system has been depicted in Fig. 10.1.

Although most of the nutrient elements have their origin from the soil, atmosphere may also contribute to plant nutrition. Rainfall is the source of several elements in their dissolved states which may add to the soil reservoir apart from being washed away into the adjacent water bodies. Nitrogen may also be fixed by soil residing microbes (symbiotic or free-living) by virtue of their nitrogenase enzyme systems through biological nitrogen fixation. More than often extensive scale fertilization is made to the soil or crop itself, which may return to the soil after the decomposition of plant residues—all of these processes contribute to dynamic soil–plant relationships. Earth surface contains igneous rocks produced from molten magma over several millions of year. The transformation of these rocks into sedimentary and metamorphic rocks and further weathering results in the formation of soil. The soil constituents in the form of sand, silt, and clay vary in their proportion resulting in variation of texture of soils and indirectly their water and nutrient retention capacity. The clay types in the form of expanding and non-expanding clays like montmorillonite, illite, chlorite, kaolinite, vermiculite, etc. may retain vast quantities of the nutrients on their edges, lattice hole, or interlayer spaces of the tetrahedral and octahedral sheets.

Additionally, under some chemical conditions of the soil calcium (alkaline), iron or aluminium (acidic) silicates may be present in huge quantities that sorb the essential plant nutrients. Desorption of the nutrients either by the cation exchange phenomenon or non-exchangeable transformations results in the nutrients to be bioavailable. Soil organic matter also acts as a repertory of metals by retention on the surface of carboxylic and phenolic functional groups of the organic moieties. Microbes decompose these materials and release the nutrients into plant-available form by mineralization. The groundwater aquifer and soil minerals may also contribute different heavy metals like cadmium, chromium, mercury, lead, arsenic that when contributes to the plant-available solution phase may create commotion in the plant system. The soil solution phase, remaining in dynamic equilibrium with the exchangeable and non-exchangeable phases, contributes to plant availability through a large number of biochemical mechanisms (Kuzyakov and Xu 2013; Dotaniya and Meena 2015; Zhu et al. 2016).

10.2.2 Factors Influencing This Dynamic Soil–Plant Relationship

From the preceding section, it can quite evidently be stated that adequate and timely availability of the essential plant nutrients from the soil is pivotal for ensuring better crop stand and establishment. Thus research on assessment of nutrient status of soil before crop cultivation is gaining tremendous value for fertilization. For most of the nutrients, only a small portion is bioavailable and several soil properties influence the chemical form, distribution, and mobility (Alloway 2005; Marschner and Rengel 2012). The significant influencers are soil texture, organic matter, redox potential,

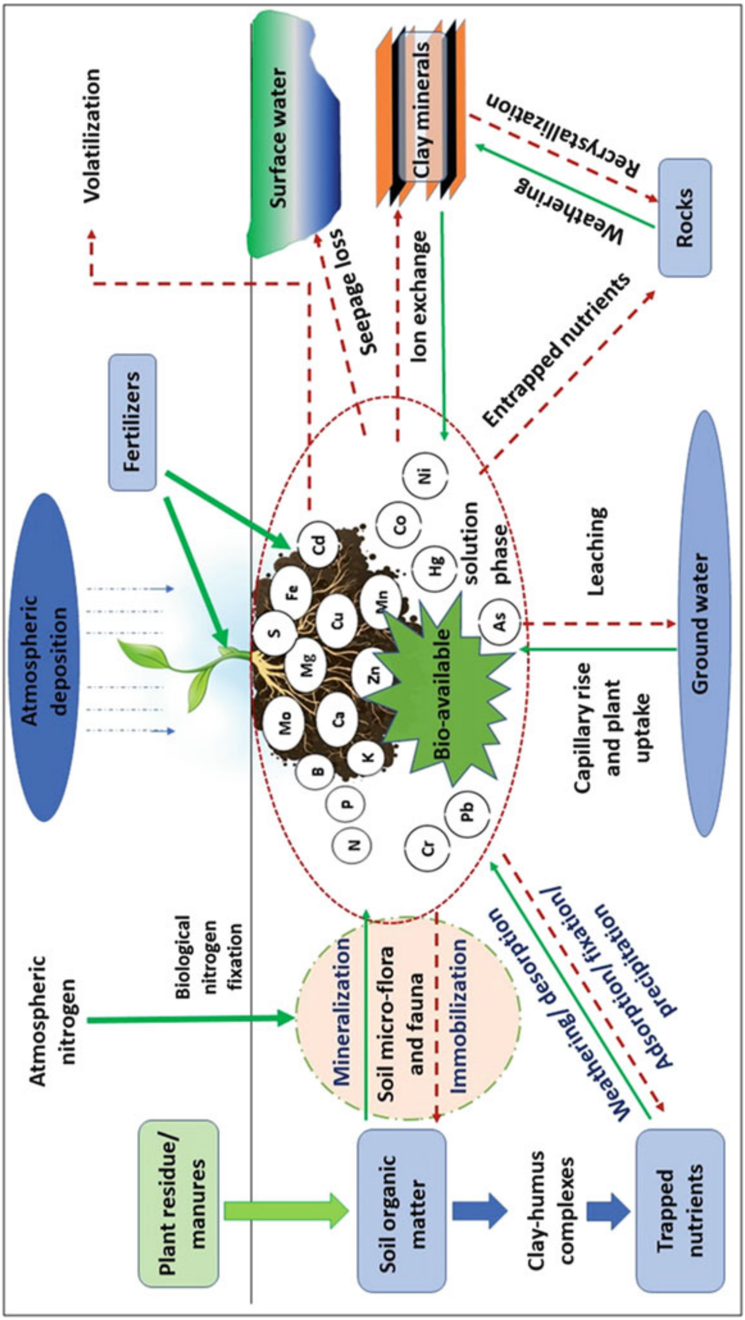

Fig. 10.1 A comprehensive overview of the dynamic soil–plant nutrient relationships

pH, cation exchange capacity, ion contents, moisture, temperature, microbial activities, etc. CEC of clay and organic matter influence the phytoavailability of nutrients. At low pH, some elements like Al, Fe may reach toxic levels and deficiency of P, Mo, etc. and leaching of basic cations may aggravate. Similarly, elevated pH results in the deficiency of Zn, Cu, and Mn (George et al. 2012). The particle size distribution of the soil influences the pattern of nutrient and water retention properties of the soil, as evident by low retention and higher leaching for sandy soils. Soil organic matter in conjunction with aeration, moisture, and temperature influences the microbial activity and the nutrient availability by biogeochemical cycling (Mikkelsen et al. 2020).

Accurate measurement of the plant-available pools of each of the nutrient warrants soil testing protocol for viable crop correlation based fertilizer recommendation. The most common estimation protocol is testing the most suitable extractant that can presumably imitate plant uptake. Thus soil testing for soil fertility mediated plant nutrition research is a tantalizing issue.

10.3 Traditional Approaches to Soil Elemental Analysis

10.3.1 A Brief Idea of the Different Approaches

Soil analysis has emerged as a recognized division of soil science since the early 1940s, with the evolution from survival to production agriculture (Jones Jr 1998). It is used to know the status of nutrients present in soil and to recommend fertilizers to crops. Soil contains a massive amount of nutrients far exceeded than crop requirement. However, the plant-available forms of nutrients matter for sustainable crop production. Several soil analysis methods have been developed by scientists for determination of plant-available nutrients (Raun et al. 1998). In those methods various reagents are used to extract plant-available nutrients. Efficiency or accuracy of methods mostly depends on extractant. As per Lindsay and Cox (1985), extractant must mimic the plant roots in extracting the nutrients from the soil as well as

- Point out the critical levels of bioavailable nutrients in soils, below which plants may manifest inadequacy.
- Function as a guiding mechanism for judicious recommendations of fertilizer to check the shortage of supply or deficiencies.
- Ascertain the magnitude of toxic, or potentially toxic, nutrients concentration in the soil under research for a specific space.

Soil analysis during early years, detailed analysis of total nutrient in the soil instead of available form, had restricted usage in soil fertility management practice (Peck 1990). Later scientists attempted to evolve an advanced extracting reagent or solution based on uptake pattern of plant roots. This purpose then exposed the principle of recognizing the share of contribution and forms of soil nutrients to plant nutrition and operational function of an extractant rely on to count all or a proportion of those forms (Peck 1990). Specialized extractants were developed and advanced for every single nutrient, some still in use, which became adopted as the standard for different regions (Dahnke 1980; Peck 1990).

During soil testing, extractant will adhere to soil for few minutes, whereas plant roots in the field are in contact with the soil for an entire growing season. Hence, it is difficult for an extractant to be the exact replica of the way extraction of nutrients occurs by roots. Besides, interactions of soil and plant roots vary owing to many factors like soil moisture, temperature, and nutrient content of soil throughout the crop growing season, etc., which is immensely strenuous to duplicate in the laboratory condition.

10.3.2 Underlying Principles of Nutrient Extraction by Extractants

There are many methods for the estimation of available nutrient content in the soil. These nutrient pools are reserves or idle, potentially mineralizable, or an available fraction which during the cropping cycle becomes plant available (Stockdale et al. 2002). Nutrients in soil remain in different pools broadly as plant-available form or labile pool and plant unavailable form or non-labile pool. Extractants works on different principles, as follows:

10.3.2.1 Intensity and Capacity Factors

Soil nutrients remain into pools as discussed above. Intensity and capacity factors represent the quantity of nutrient present in labile pool or in soil solution and quantity of nutrient that can readily come into labile pool from non-labile pool, respectively. Most soil test methods comprised of shaking a sample of soil with an extracting solution for a specified period. Then the suspension is filtered and measured for the quantity of nutrient that comes into solution. These factors must be reflected in soil test for better results. An extractant which represents the dissolution of non-labile pool is ideal. This principle best works for macronutrient cations like potassium (extractant neutral normal ammonium acetate), whereas, for micronutrients, it does not suit as the quantity in soil solution is very low, quantity in non-labile pool is also low. Hence, most of the common nutrient extractants are developed on acid or base, complexing or chelating agent principle.

10.3.2.2 Acid or Base Extractions: Dissolution and Oxidation Phenomena

Acids and bases can dissolve nutrients from non-labile pool or unavailable form. Concentrated acid and bases generally do not serve as ideal extractant as they dissolve excess nutrients from the unavailable form than plant do. Hence, dilute acids and bases are generally used as soil test extractants. Dilute acids have been extensively used on acid or acidic soils, while bases often used for alkaline soils. Bray 1, Bray 2, and citric acid are the extractants for available phosphorus in acid soils and Olsen reagent used in neutral to alkali soils. Metals often in soil solid undergo dissolution process to come into the solution phase, chemically either being solubilized or oxidized by the reagents. Oxidation and/or reduction can serve this phenomenon of releasing a large quantity of heavy metals from the soil facilitating extraction process.

10.3.2.3 Chelating and Complexing Agents

For assessing nutrients, extractants working on chelating and complexing principle have been used extensively. One must be careful about selecting extractant (its concentration and shaking time) as critical nutrient concentration limits and toxicity limits are narrow for acid soils. Often chelating and complexing agents are used by including dilute acids. The mechanism of complexation is based on a simple ligand exchange phenomenon where metal is paired with the ligand altering the charge on the surface effectuating the equilibrium among solution and exchangeable phases. Further, the principle of ion exchange plays an invincible role in addressing the equilibrium, especially a significant contribution being made by ion exchange resin. The basis of these procedures is metal as being removed from solid soil phase by desorbing cation is facilitated by mass action to remove all the metals in the soil solution (McLaughlin et al. 2000).

10.3.3 Use of Different Single Extractants Protocols

While selecting the extractant one must be careful as extractants mostly depend on soil type and soil reaction. One extractant cannot be used in all type of soils. The extractants for acidic soil reaction are not similar to that of alkaline. As for example, for phosphorus, in neutral to alkali soils, Olsen's reagent will be useful. Carbonate activity in soil is raised, resulting in decreased activities of Ca, Fe, and Al. Thus PO_4 from soil surface of Ca, Fe, and Al phosphate is brought into solution. In acid soils, the released H^+ will neutralize bicarbonate. In this case solubilization effect of H^+ on soil phosphorus and the ability of F (as in Bray reagent) to lower the activity of Al ion to a lesser extent than those of Ca and Fe ions in the extraction system is evident.

DTPA is useful in alkaline and calcareous soils. It is designed to avoid excessive dissolution of $CaCO_3$ with the release of occluded micronutrients. At a selected pH of 7.3, approx. 3/4th of TEA gets protonated. It exchanges Ca and Mg from exchangeable sites. Hence Ca in solution increases and suppresses dissolution of $CaCO_3$ in calcareous soils. For boron, mannitol, $CaCl_2$ method is suitable for alkali and calcareous soils, while salicylic acid for acid soils is best suited for similar reasons.

In the pretext of variation in the working mechanisms and variation in edaphic properties pertaining to plant rhizosphere, a large number of extractants have been tested over the years and elucidated in Table 10.1.

Table 10.1 A detailed description of the single element extraction process used in soil–plant nutrition research

Nutrient	Extractant	Developed by	Possible mechanism
Nitrogen	0.32% Potassium permanganate (alkaline)	Subbiah and Asija 1956	Permanganate provides nascent oxygen in the presence of alkali media, which decompose organic matter in soil and mineralize N
	Hot water	Keeney and Bremner 1966	Water soluble N (at high temperature) will be extracted
	Hydrochloric acid	Peterson et al. 1960	Acid digests organic matter and liberates N
	Sulphuric acid	Peterson et al. 1960	
	Dilute barium hydroxide solution	Setatou and Simonis 1996	N liberated by alkali digestion will be analysed
	Alkaline calcium hydroxide	Prasad 1965	
	0.01 M $NaHCO_3$	Chaudhry et al. 1964	
	Normal sodium hydroxide	Cornfield 1960	Ammonia liberated will be analysed
Phosphorus	Water	Olsen and Watanabe 1970	Easy solvable portion of P in soil
	0.01 M $CaCl_2$	Aslyng 1964	Dilute salt extractable P will be analysed
	0.03 N NH_4F + 0.025 N HCl	Bray and Kurtz 1945	Solubilization effect of H^+ on soil P and F lowers the activity of Al^{3+}
	0.1 N HCl + 0.03 N NH_4F	Hylander et al. 1999	
	0.5 M $NaHCO_3$ pH = 8.5	Olsen 1954	Bicarbonate decreases the activity of Ca, solubilizes calcium phosphate
Potassium	Neutral normal ammonium acetate	Schollenberger and Simon 1945	Ammonia replaces K on exchange sites
Calcium	Neutral normal ammonium acetate	Schollenberger and Simon 1945	Ammonia replaces Ca on exchange sites
	Water	Richards 1954	Easy solvable portion of Ca in soil
	EDTA	Tucker and Kurtz 1961	Complexation of EDTA and titrimetric estimation
Magnesium	Neutral normal ammonium acetate	Schollenberger and Simon 1945	Ammonia replaces Mg on exchange sites
	Water	Richards 1954	Easy solvable portion of Mg in soil
	EDTA	Tucker and Kurtz 1961	Complexation of EDTA and titrimetric estimation

(continued)

Table 10.1 (continued)

Nutrient	Extractant	Developed by	Possible mechanism
Sulphur	0.15% $CaCl_2$	Williams and Steinbergs 1959	Chloride ions displace adsorbed sulphate
	1 M NH_4OAC	McClung et al. 1959	Extracts soluble sulphate plus a fraction of adsorbed sulphates
Micronutrients	DTPA+$CaCl_2$+ TEA	Lindsay and Norvell 1978	Avoid excessive dissolution of $CaCO_3$ with release of occluded micronutrients
Boron	Hot water	Berger and Truog 1939	Mass action to access the easily solvable B from soil
	0.01 M $CaCl_2$+ 0.05 M Mannitol	Cartwright et al. 1983	Pertaining to ligand exchange mechanism for B from alkali and calcareous soils
	0.1 M Salicylic acid	Datta et al. 1998	Pertaining to ligand exchange mechanism for B from acid soils
Molybdenum	Acid ammonium oxalate (pH −3.0)	Grigg 1953	Extraction of Mo from interfering ions like Ti, V, Cr through pH mediated stable complexation

10.3.4 The Demerit of Traditional Extractants and their Workload

Soil test result gives a brief idea of soil fertility status and immaculate the process of fertilizer recommendations for most of the time. Hence timely communicating the results to the farmers will be useful for maintaining sustainable crop production and healthy soils. A considerable number of samples from farmer fields come for soil testing every year to soil testing laboratories. Soil analysis by traditional methods will consume more time, as for individual nutrient analysis process is quite different from others. Conversely, the workforce with the laboratories is limited. With these low human resources, it is challenging to communicate the results in advance to purchase of fertilizers by farmers. Moreover, the cost associated with analysing one soil sample for OC, N, P, and K costs near about Rs. 85–90 per sample (only chemicals cost) which widely vary country wise. In the pretext of the burgeoning workload and limited human resources, a viable alternative is to be sought.

10.4 Current Researchable Advances: Delving into Multinutrient Extractants

For overcoming the inadequacy of traditional extraction, multinutrient research is cropping up:

10.4.1 Concept of Multinutrient Extractant

The chemical methods for extracting different plant essential nutrients generally followed in most of the soil testing laboratories are quite efficient and precise in determining the available content of these nutrients in the soil but involve several extractants and protocols for extraction. However, such methodologies for extraction of nutrients from soil through specific extractants are more time-consuming, laborious, tedious, as well as costly because of more use of chemical reagents, glass goods, and energy. To this end, multinutrient extractants offer a suitable alternative to the traditional routine extraction procedure, as more than one nutrient can be extracted by a single solution (Bibiso et al. 2015) involving less time and labour. Several numbers of extractants are there to extract phytoavailable forms of many essential elements at a time without compromising accuracy for one element to another. In order to get a rapid, reproducible, inexpensive, non-toxic extraction procedure which will be adaptable to soils and extract the labile forms of nutrients, choice of a suitable multinutrient extractant is of utmost importance. However, such extractants must be verified for the estimation of available nutrients for a particular soil type based on their interrelationship with various soil properties, existing analytical protocols, and most importantly the crop responses for their suitability and accuracy (Sharma et al. 2018).

10.4.2 Chronological Advances in the Field of Universal Multinutrient Extractant

Universal soil extractants are referred to as a single extractant to extract more than one category of nutrients (both primary nutrients and micronutrients) and/or ions for use on a variety of soils with the concentration so extracted can be used for soil fertility assessment (Jones Jr 1990). All these extraction reagents have considerable advantages in today's soil testing laboratories, viz. the use of advanced multi-element analysers like inductively coupled plasma-atomic emission spectrometer (ICP-AES) (Soltanpour et al. 1983) and the automated flow injection analysers (Ranger 1981) for assaying both the major elements and micronutrients in the prepared soil extracts.

1. *Morgan extraction reagent*
   The first universal soil extractant was developed by Morgan (1941, 1950) with the composition being 0.73M sodium acetate ($NaC_2H_3O_2$) solution buffered at pH 4.8 which was used widely during 1950 to early 1960s (Jones Jr 1973, 1990) for the determination of several elements, viz. NH_4, NO_3, P, K, SO_4, Ca, Mg, Fe, Mn, Zn, Cu, Pb, As, Hg, and Al except Na. The pH 4.8 was taken to simulate the CO_2 saturated soil solution adherence to the plant root. Solution with this pH would behave as a mild solvent for aluminium and iron phosphates along with other minerals that might release important plant nutrients. However, it is of minimal use today because of the search for an alternative and better soil test

methods, particularly for soil P (Bray and Kurtz 1945; Olsen 1954; Mehlich 1953; Jones Jr 1998).

2. *Mehlich No. 1 (M 1) reagent*
   Mehlich no. 1 (M 1) extractant was introduced in 1954 and is still in wide use today. The extraction reagent is composed of a mixture of 0.05N HCl in 0.025N H_2SO_4. Being a double acid (DA) extractant it meets much of the requirements of a mass analyses method for the determination of P, K, Ca, Mg, Na, Mn, and Zn in acid sandy soils. However, DA is not recommended for calcareous soils or on acid soils where rock phosphate was applied in recent past as it may extract P in significant excess amount than those extracted with routinely used extractants, viz. Bray 1 and Olsen under such soil condition (Kumawat et al. 2017).
3. *Mehlich No. 2 (M 2) reagent*
   Mehlich (1978) further modified M 1 reagent to facilitate simultaneous extraction of various nutrients over a broad range of soil properties which was composed of 0.2N NH_4Cl–0.2N HOAc–0.015N NH_4F–0.012N HCl at pH 2.5.
4. *Wolf reagent (Modified Morgan's reagent)*
   Wolf (1982) modified the Morgan extractant by adding DTPA (diethylenetriaminepentaacetic acid) chelate to the extractant for the estimation of cationic micronutrients, viz. Zn, Cu Fe, and Mn. The composition of the extractant is a mixture of 0.073M sodium acetate ($NaC_2H_3O_2$), 0.52N acetic acid (CH_3COOH), and 0.001M diethylenetriaminepentaacetic acid (DTPA) buffered at pH 4.8. Although like previous Morgan extractant, Morgan-Wolf extractant has proved somehow unacceptable for wide use due to high Na concentration, which creates a problem by frequent fouling of the burner head of atomic absorption spectrophotometer (Jones Jr 1990).
5. *Mehlich No. 3 (M-3) reagent*
   In 1984, Mehlich further modified Mehlich No. 2 extractant for its extensive use in a broad range of soils, particularly for acid soils. EDTA chelate was included in M-3 to enhance the extracting power Zn, Mn, and particularly Cu (Mehlich 1984). In previous composition, the chloride in HCl and NH_4Cl was highly corrosive for laboratory instrumentation. Substituting nitrate for chloride ions achieved this objective by minimizing the corrosiveness (Kumawat et al. 2017). The resultant extracting solution has been designated as Mehlich 3 (M-3) composed of 0.2N CH_3COOH–0.25N NH_4NO_3–0.015N NH_4F–0.013N HNO_3–0.001M EDTA; buffered at pH 2.5 $\pm$ 0.1. It includes the combinations of EDTA and dilute acids which extract sizeable amounts through solubilizing organic and oxidized pools for a wide range of nutrients. Initially, Mehlich 3 was suggested for use in acid soils, though it has been established for use in alkaline soils also because both acetic and nitric acids have strong dissolving and extracting power from $CaCO_3$ (Sawyer and Mallarino 1999). Mehlich 3 executes satisfactory performance as compared to DTPA method (Lindsay and Norvell 1978) for micronutrients worldwide and proved to be a convenient alternative to hot water method for B extraction with closer interrelationship when soil pH was incorporated (Walworth et al. 1992).

6. *Modified Mehlich No. 3 reagent*
   Mehlich 3 extractant was further modified by Yanai et al. (2000) for the simultaneous extraction of macro- and micronutrients in arable soil. The composition of the extractant was 0.2M CH_3COOH, 0.25M NH_4Cl, 0.005M $C_6H_8O_7$ (citric acid), 0.05M HCl adjusted to pH 1.3. Several advantages of the new extractant over Mehlich 3 include 0.005M citric acid used in the extractant to exclude the F^- ions. F^- in the Mehlich 3 may dissolve K from the glass bottles and EDTA in Mehlich 3 precipitates after continued storage, so HCl mediated decrease in pH in the new extractant was categorized.
7. *Ammonium bicarbonate-DTPA extractant (AB-DTPA)*
   The AB-DTPA multinutrient extraction reagent for soil testing was introduced by Soltanpour and Schwab (1977) for simultaneous extraction of several nutrients, viz. K, P, NO_3, Mn, Fe, Zn, and Cu from alkaline soils. The solution was composed of 1M ammonium bicarbonate (NH_4HCO_3), 0.005M diethylenetriaminepentaacetic acid (DTPA) adjusted to a pH of 7.6. CO_2 (g) is released during extraction with AB-DTPA and the soil-extractant solution pH increases from 7.6 to 8.5. In this high pH, calcium carbonate and bicarbonate precipitate which allows the labile phases of calcium phosphate to release and dissolve in the solution phase. It is the principle for inclusion of HCO_3 anion in the DTPA extracting solution to measure phosphate and other anions like sulphate, arsenate, molybdate, etc. by releasing through desorption and dissolution mechanism from the surface of clay size minerals (Soltanpour 1991). However, the above extractant cannot usually determine S and B and hence require single nutrient extraction (van Raij 1994). Again, this soil extraction process may not be suitable for acid soils of the tropics as it was formulated to simulate the chemical environments of alkaline range of soils. In this procedure, carbon black was used to get the clear extractant for chromatographic nutrient measurements of a few nutrients along with the acid method of nitrate estimation. However, this could create erroneous results due to adsorption of metal chelates in the surface of carbon black, especially when particle size is not kept constant (Lindsay and Cox 1985). So carbon black should not be used with AB-DTPA extraction processes.
8. *Acid ammonium acetate-EDTA extractant (AAAc-EDTA)*
   The acid ammonium acetate-EDTA extractant as a universal extractant was developed at Agricultural Research Centre of Finland by Sippola (1994). The multinutrient extractant was developed initially for the extraction of micronutrients, viz. Fe, Mn, Zn, Cu Mo, and Co; however, it has also been reported to be capable of extracting P and K simultaneously in acidic soils. The extraction solution is made of 0.5N concerning both ammonium acetate and acetic acid and 0.02M Na_2EDTA adjusted to a pH of 4.65 (Lakanen and Erviö 1971).
9. *Kelowna multinutrient extractant*
   Kelowna extracting reagent or Kelowna-1 was first formulated as a multinutrient extractant in British Columbia. The extractant was appraised for use in calcareous and non-calcareous soils with neutral to alkaline pH. The extractant is

comprised of 0.25M acetic acid + 0.015M ammonium fluoride (Van Lierop 1988), which was later modified (Kelowna-2) by the addition of 0.25M ammonium acetate (Qian et al. 1994). Ashworth and Mrazek (1995) slightly customized it by intensifying the concentrations of ammonium acetate and acetic acid to 1.0M and 0.5M, respectively (Kelowna-3).

10. *Hot water percolation (HWP) method*
    The hot water percolation method (HWP), a comparatively new and easily applicable soil extraction method has been developed by using the coffee percolator principle (Füleky and Czinkota 1993). With this method, the bioavailable, desorbable, as well as readily soluble nutrient elements are extracted by hot water (102–105 °C) at 120–150 kPa pressure. Nearly, all the elements can be extracted through this method in assessable range but the macronutrients in appreciable quantities. The amounts of nutrients extracted with this method are in strong association with those of routine soil testing methods and also with the nutrient uptake by several crops.
11. *Resin extraction method*
    McLaughlin et al. (1994) found out the relationships between elements extracted using resin-bead and resin membrane method and conventional method. A strong correlation between elements concentrations extracted by the conventional methodology of routine soil analysis and resin methods was evident, although it lacks ample Al extracting power than the 1M KCl method.
12. *H3A-1 method*
    A new soil extractant, namely H3A was developed by Haney et al. (2006) which can extract NH_4, NO_3, and P from widely varied soil in respect of organic carbon (C), soil pH, and clay content. It extracts P simultaneously from both acid and calcareous soils and so obliterates the need for different procedures of phosphorus (P) extraction for acid and calcareous soils. The extractant is a mixture of organic root exudates, lithium citrate, and two synthetic chelators (DTPA, EDTA). The composition and concentration of the extractant is lithium citrate (0.02M), citric acid (0.0024M), malic acid (0.004M), oxalic acid (0.004M), 0.002M EDTA, 0.001M DTPA, and pH maintained around 5.0. This single extractant can determine P, NO_3-N, NH_4-N. Advantages of this extractant are that this would extract the nutrients near soil pH $\pm$ 1 unit by dissolution and ligand exchange mechanism from organic root exudates. Li-ions would function like K for replacing NH_4 from exchangeable soil sites. Organic acids of the extractant make it more convenient to use across a wider range of soil pH.
13. *H3A-2 method*
    H3A-1 method was modified by Haney et al. (2010) to reduce the extractable Fe and Al and also to improve the nutrient extracting interrelationships with other regular and routine soil extractants. A strong association with NH_4-N, NO_3-N, P, PO_4, Ca, K, and Zn has been observed through correlations when compared to the original H3A-1 method as well as conventional soil test protocols, viz. Olsen, ammonium acetate, water, KCl, Mehlich 3, Bray 1, and DTPA. The composition and concentration of the multinutrient extractant is

2 g L^{-1} lithium citrate (0.02M), 0.6 g L^{-1} citric acid (0.0024M), 0.4 g L^{-1} malic acid (0.004M), 0.4 g L^{-1} oxalic acid (0.004M) buffered at pH value of 4.4.

Apart from these some sequential extraction scheme has also been opted for:

1. *DTPA extractant*
   Lindsay and Norvell (1969, 1978) developed the DTPA (diethylenetriaminepentaacetic acid) micronutrient soil test for simultaneous extraction with the chemical composition of the extractant being 0.005M DTPA, 0.01M $CaCl_2.2H_2O$, 0.1M triethanolamine (TEA) adjusted to a soil pH of 7.3. The extracting reagent was developed to simulate the chemical environments expected in neutral to calcareous soils for dissolution of $CaCO_3$. Therefore, the equilibrium develops between 0.005M DTPA and free Ca^{2+} which regulate the free DTPA ligand activity and supply an adequate reserve of DTPA to bind small amounts of the micronutrient metals without disturbing its capability to extract additional metals (Norvell 1984). However, this procedure may not be as suitable in highly weathered acid soils. DTPA was proved to show an effective simulation of a wide range of metal cations, viz. Zn, Mn, Al, Cu, Cd, and Ni including the highly insoluble Fe ion.
2. *Modified Kelowna (KM extractant)*
   This soil testing procedure was described by Ashworth and Mrazek (1995) for simultaneous extraction of plant available K and P in soil which uses an aqueous solution comprised of acetic acid, ammonium fluoride, and ammonium acetate. The basic advantage of the extractant over the other extractants is its analytical ease and applicability to calcareous soils.

10.4.3 Classification of Universal Extractants Used for Soil Multinutrient Research

Over the years, a large number of universal multinutrient extractant have been tested in different global areas for soils having variation in properties. The present study tends to conglomerate all such studies and have been elucidated in Table 10.2.

10.5 Use of Multinutrient Extractants in Heavy Metal Research

One of the severe threats to agricultural productivity and assuring dietary food security is the heavy metal contamination of a wide range of global agricultural lands. In a broader sense, heavy metals correspond to a group of metals and metalloids possessing the potential of ecotoxicity. The aggravating concern about the soil–plant–food chain continuum in conjunction to ingestion, inhalation, and dermal contact impairs the human health through carcinogenic, mutagenic, and teratogenic consequences (Hou et al. 2017) in different pockets of the study area. A large number of heavy metals find their entry through soil system having a wide

Table 10.2 Classification of various multinutrient soil extractants based on extraction medium, soil: solution ratio and shaking time

S. no.	Extractant used	Soil types	Extractant composition	Soil: extractant	Shaking time (min)	Reported nutrients extraction	Firstly reported from	Reporting literature
1	Morgan reagent	Acidic soil	0.73 M NaOAc and 0.025 M HCl, pH 4.8	1:4	15	NO_3, NH_4, P, K, S, Ca, Mg, Fe, Mn, Zn, Cu	Soils of Storrs, Windsor city, Connecticut state, USA	Morgan 1941
2	Mehlich No. 1	Acid sandy soil	0.05 N HCl in 0.025 N H_2SO_4	1:4	5	P, K, Ca, Mg, Na, Mn, and Zn	North Carolina State, south-eastern region of the USA	Mehlich 1953
3	Mehlich No. 2	Wide range of soils	0.2 N NH_4Cl–0.2 N HOAc–0.015 N NH_4F–0.012 N HCl at pH 2.5	1:10	5	P, K, Ca, Mg, Na, Mn, and Zn	Mountain, Piedmont and Coastal Plains of North Carolina	Mehlich 1978
4	Wolf reagent or Modified Morgan's reagent	Acidic soil and organic soils	0.073 M sodium acetate ($NaC_2H_3O_2$), 0.52 N acetic acid (CH_3COOH), and 0.001 M diethylenetriaminepentaacetic acid (DTPA) buffered at pH 4.8	1:4	15	N, P, K, S, Ca, Mg, Fe, Mn, Zn, Cu	High CEC soils of countries like Colombia, Guatemala, Mexico, Puerto Rico in addition with low CEC soils of Florida	Wolf 1982
5	Mehlich No. 3 (M-3) reagent	Acidic soil	0.2 N CH_3COOH–0.25 N NH_4NO_3–0.015 N NH_4F–0.013 N HNO_3–0.001 M EDTA pH buffered at 2.5 ± 0.1	1:10	5	P, K, Ca, Mg, S, B, Zn, Fe, Cu, Mn	105 soil samples from North Carolina State, Southern East USA	Mehlich 1984
6	Modified Mehlich No. 3 reagent	Arable land soil	0.2 M CH_3COOH, 0.25 M NH_4Cl, 0.005 M $C_6H_8O_7$	1:10	30	Macro- and micronutrients in arable soil	49 soil samples in various districts of Japan and Korea	Yanai et al. 2000

			(citric acid), 0.05 M HCI adjusted to pH 1.3					
7	Ammonium bicarbonate-DTPA (AB-DTPA)	Alkaline soil	1 M ammonium bicarbonate (NH_4HCO_3), 0.005 M DTPA, and adjusted to a pH of 7.6	1: 2	15	P, NO_3, K, Fe, Mn, Zn, and Cu	Alkaline soils of Colorado states, Western USA	Soltanpour and Schwab 1977
8	Acid ammonium acetate-EDTA (AAAc-EDTA)	Acidic soil	0.5 N with respect to both NH_4OAc and HOAc and 0.02 M Na_2EDTA, pH 4.65	1:10	60	P, K, Fe, Mn, Zn, Cu Mo, and Co	Agricultural Research Centre of Finland	Lakanen and Erviö 1971; Sippola 1994
9	Modified Morgan	Acidic soil	0.62 N NH_4OH and 1.25 N HOAc, pH 4.8	1: 5	15	P, K, Ca, Mg, Zn, Fe, Cu, Mn	10 soils of adjacent Vermont Agricultural Station	McIntosh 1969
10	CDTA-Glycerol method	Wide range of soils	0.002 M CDTA + 0.05 M Glycerol + 0.1 M NH_4OAC + 0.01 M NH_4F, pH 4.8	1: 2	15	P, K, Ca, Mg, S, B, Zn, Fe, Cu, Mn	40 Rice growing soils of West Bengal state, India	Seth 2016
11	Kelowna multinutrient extractant	Calcareous, neutral to alkaline soil	0.25 N HOAc + 0.015 N NH_4F	1:10	5	NO_3, P, K, Na	23 acid and calcareous soils of Kelowna city, British Columbia province, Canada	Van Lierop 1988

range of sources, either natural/geogenic (parent material weathering, groundwater uplift) or anthropogenic (metal smelting, sewage sludge, solid waste disposal, pesticides, fossil fuel combustion, etc.) sources (Sanyal 2017) and depend on many soil physic-chemical properties, viz. pH and organic carbon (Saha et al. 2018b). The emanating problem necessitates a thorough evaluation and monitoring of the situation through chemical and instrumental characterization. In some cases, a single soil may be contaminated with a large number of heavy metals. However, the fact that each heavy metal detection has a cumbersome protocol of sample extraction, preparation, and analytical procedures. The research warrants a new strategy emanation involving multinutrient extraction by which several heavy metals can be detected in one attempt and thus assessment of status of the pollution, the risk associated with its consumption, safe detectable limit calculation as well as drawing possible mitigation approaches would be favourable. Different multinutrient extractants have been attempted for heavy metal analysis, a few of which has been elucidated in Table 10.3.

10.6 Advanced Instrumentation Techniques and Their Analytical Workability

With the advancement of our desire, we are habituated to contaminate the soil either intentionally or unintentionally. Soil pollution is caused by industrial effluents, pharmaceutical wastes, packaging materials even from electronic wastes. Toxic metals and metalloids contaminate human food chain from polluted soils (Järup 2003; Sparks 2005; Reddy et al. 2012; Sarkar et al. 2020). Thus, advanced and sensitive measurement techniques with less workload are necessary to achieve proper monitoring of the environment and human health. As a consequence, the extractability of different elements solely depends on the chemical properties of the desired element to be tested. Most of the literature reviewed related to trace or heavy metals, metalloids, pharmaceutical wastes, human health risk assessment, polluted area delineation, and other soil pollution aspects used (1) atomic absorption spectrometry (AAS), (2) microwave plasma-atomic emission spectrometry (MP-AES), (3) inductively coupled plasma-optical emission spectrometry (ICP-OES), and (4) inductively coupled plasma-mass spectrometry (ICP-MS) as advanced instrumentation techniques (Donati et al. 2017; Lu et al. 2019; Vyhnanovský et al. 2019; Fujihara and Nishimoto 2020). Thus, we have focused on these four instruments along with ion specific electrodes and discussed the working principle and mode of operation in the ensuing sections.

10.6.1 Atomic Absorption Spectrometry

Though optical spectrometry has a pervasive history and started as early as 1672 from the experiment of Sir Isaac Newton, who separated the sunlight beam into a different colour spectrum with a transparent glass prism (Koirtyohann 1991).

Table 10.3 Multinutrient extractants in soil heavy metal research

S. no	Extractants used	Best extractant	Heavy metal extracted	Crop	Study area	Reported by	Notable findings
1.	Mehlich-3 and DTPA	Mehlich-3	Cd, Ni, Pb	Soil based (Non-crop specific)	Coal mine soils of As Pontes (Spain)	Monterroso et al. 1999	Most significant relationship $r = 0.87$ and 0.74 for Cd and Pb
2.	Mehlich-1, 0.1 M HCl, DTPA	0.1 M HCl	Cd, Pb	Rice and soybean	Surface oxisols of Brazil	Silva et al. 2012	HCl had best correlation $r = 0.934$ and 0.864 for Cd and Pb
3.	Mehlich-3, AB-DTPA, DTPA-TEA, Mehlich-2, $CaCl_2$, HCl	DTPA-TEA	Pb, Zn	Bean	Mining sites of Central Iran	Hosseinpur and Motaghian 2015	Chelation principle best attributed to heavy metal extraction
4.	Mehlich-3	Mehlich-3	Cd, Pb, Ni	Soil, lettuce, dry bean	Latosols of Brazil	Fontes et al. 2008	Best values of $R^2 = 0756$, 0.494, and 0.686 were observed for Cd, Pb, and Ni
5.	$Sr(NO_3)_3$, $CaCl_2$, $NaNO_3$, NH_4OAc, $LiNO_3$, NH_4NO_3, $MgCl_2$, HOAc, NH_4-EDTA	NH_4-EDTA	Ni, Cd, Pb, As, Se	Deschampsia spp.	Sudbury, Ontario, Canada	Abedin et al. 2012	No single extractant emerged best but chelation principle best attributed to heavy metal extraction ($r \geq 0.7$)
6.	DTPA, AB-DTPA, Mehlich-1, Mehlich-3, 0.1 M HCl, HOAc	AB-DTPA, Mehlich-1, HOAc	Cd	African Marigold	Inceptisol, alfisol, and verisols of Uttar Pradesh, India	Sahu et al. 2016	$r = 0.954$ (inceptisols), 0.957 (alfisols), 0.944 (vertisols)
7.	AAAc-EDTA	AAAc-EDTA	Cd, Cr, Ni, Pb	Soil based (Non-crop specific)	Soils of Finland	Sippola 1994	Comparison with traditional methods yielded significant results
8.	DTPA, Mehlich-1, Mehlich-3, 0.1 M HCl	0.1 M HCl	Cd, Pb	Aquatic plants like cattails, maidencane,	Coal mine soils of Alabama, USA	Sistani et al. 1995	0.1 M HCl provided better correlation as compared to

(continued)

Table 10.3 (continued)

S. no	Extractants used	Best extractant	Heavy metal extracted	Crop	Study area	Reported by	Notable findings
				pickerelweed, and bulrush			others in the nondetectable range
9.	EDTA, $CaCl_2$, Low molecular weight organic acids	EDTA (although not significant)	Ni, Cu, Zn	Barley	Spain	Soriano-Disla et al. 2010	Sewage sludge polluted soils could not yield significant relationships ($r < 0.5$)
10.	0.1 M HCl, DTPA, Mehlich-1, Mehlich-3	Mehlich-3 and DTPA	Pb, Ni	Corn and Sudan grass	Alabama and Decatur, USA	Xiu et al. 1991	In the sludge contaminated soils both Mehlich-3 and DTPA yielded similar result

However, AAS was conceptualized during 1955, and microprocessor-based modern AAS was developed in 1976, which further modified and advanced with progress of science (Koirtyohann 1980). Modern AAS is comprised of the radiation source, sample holder, nebulizer, atomizer, monochromatic lens, wavelength selector, detector, photo-multiplier, and indicator device. Nebulizer is responsible for creating an aerosol of analyte and solvent, thereafter, flame vapourize the solvent and excite the analyte. During excitation, valence electrons of atoms move to higher energetic orbitals and emit radiation at a signature wavelength (specific to a particular element, which it absorbs during excitation and radiates while returning to ground state) (Jeffery et al. 1989). Though flame could only excite 1–5% of atoms, the rest of the atoms absorb the light of signature wavelength radiated from hollow cathode lamp, specific for a particular element. Thus, the amount of transmitted radiation is directly proportional to atoms in excited states. Atomic absorption spectrometry follows Beer–Lambert's law and concentration of unknown sample determined by comparing with known concentration of standard. According to Beer–Lambert's law absorbance (A) is directly proportional to the molar concentration (c) of sample (when optical path length, l and molar absorption coefficient, ε are constant).

$$A = \varepsilon c l = \log_{10} (I_0/I)$$

where I_0 and I are correspondingly intensity of incident and transmitted monochromatic light.

Based on different types of atomizer AAS is classified as flame-AAS (flame atomizer), graphite furnace-AAS (graphite tube atomizer), cold vapour-AAS (high vapour pressure at normal temperature), hydride-AAS (sodium borohydride), and glow discharge-AAS (electrical conductor). Apart from this, based on radiation source AAS could be further classified in line source-AAS (LS-AAS) and continuum source-AAS (CS-AAS). The flame-AAS is the most commonly used and oldest AAS technique, where air-acetylene (~2300 °C) and nitrous oxide-acetylene (~2700 °C) are used as source of flame (Jeffery et al. 1989; Firouzabadi et al. 2017). This technique is typically used to detect elements having higher oxygen affinity, but the detection level varies from mg L^{-1} to μg L^{-1}. Graphite furnace-AAS is also known as electrothermal-AAS, which has graphite tube (typically 20–25 mm length and 5–6 mm inner diameter) operated between 1400 and 2500 °C depending on element to be determined. Graphite furnace-AAS has 2–3 times higher magnitude of sensitivity and can be able to detect from low μg L^{-1} range to ng L^{-1}. The sensitivity of As, Sb, Pb, Se, and Bi determination is further enhanced with the use of 1% acidic solution of volatile sodium borohydride ($NaBH_4$) in hydride-AAS. It simultaneously reduces the atomization temperature and enhances the detection sensitivity by 10–100 folds. However, this instrumentation requires a skilled workforce as $NaBH_4$ is corrosive, flammable, and too costly. Elements like mercury (Hg) have higher vapour pressure at normal temperature compared with other trace and heavy metals. Most suitable AAS technique used for Hg and Cd determination is cold vapour-AAS that could be able to detect at ng L^{-1} range (Lu et al. 2019).

LS-AAS typically used hollow cathode lamp of the analyte itself for better detection, but CS-AAS (deuterium lamp) is used for background correction.

10.6.2 Inductively Coupled Plasma-Optical Emission Spectrometry

The necessity of multi-element determination even at the level of parts per billion led to the development of ICP-OES at the early 1970s; however, the gradual shift from FAAS to ICP-OES started during 1980s (Donati et al. 2017). In ICP-OES, measurement of emitted lights by the elements of interest is recorded and comparing the unknown samples with known standards the respective elemental concentration is determined. ICP-OES provides lower detection limits and the option of precise multi-elemental analysis of even 70 elements at a time. In ICP-OES samples are determined by simultaneous use of plasma and spectrophotometer. Plasma is defined as a state of matter or cloud of electrons, highly ionized gas and neutral particles under continuous interaction. Typically in plasma more than 1% of carrier gas is observed in ionized state (Jeffery et al. 1989). Plasma is produced in neutral gas (e.g. Ar) under a strong electrical field either using direct current or radiofrequency (RF). The operating temperature for plasma ranges from 6700 to 14,800 °C (Jeffery et al. 1989). Based on synthesis procedure plasma is often sub-classed as direct-current plasma (DCP) and inductively coupled plasma (ICP). In DCP, plasma is produced by passing the Ar gas in the array of two graphite anode and a tungsten cathode placed in inverted 'Y' organization and temperature rises as high as 7500 °C (Skoog et al. 2007). Conversely, ICP is produced due to time-varying magnetic fields generated from high voltage time-varying electricity following Faraday–Lenz's law of induction (Montaser and Golightly 1992). However, ICP has provided higher sensitivity and lower level of detection compared to DCP with the expense of relatively higher Ar gas. Detail instrumentation and working principle of ICP-OES is elaborated in Fig. 10.2. The working principle comprises sample nebulization, aerosol formation, vapourization, atomization, ionization, and detection, respectively. The ICP produces very high temperature, which atomizes and ionizes the analyte sample. In sequence, diffraction grating provides multiple wavelengths at a time, which facilitates multi-elemental analysis. Compared to AAS, ICP-OES does not have any radiation source (hollow cathode lamp). The Ar plasma is solely responsible for vapourization, atomization, and ionization. Based on differential heat excitation analyte sample is determined through ICP-OES.

In present ICP-OES are developed considering the following recent advancements.

- *Low consumption of Ar*: Conventional ICP-OES were fitted with Fassel-type ICP torch, which generally consumes 12–20 L min^{-1} Ar gas for plasma generation and cooling. Since 2005, modern ICP-OES is equipped with redesigned bulb-shaped static high-sensitivity ICP torch that typically consumes 0.05–1.00 L min^{-1} Ar (Klostermeier et al. 2005; Donati et al. 2017). A homogeneous temperature regime in the redesigned ICP-torch plasma provides more sample residence

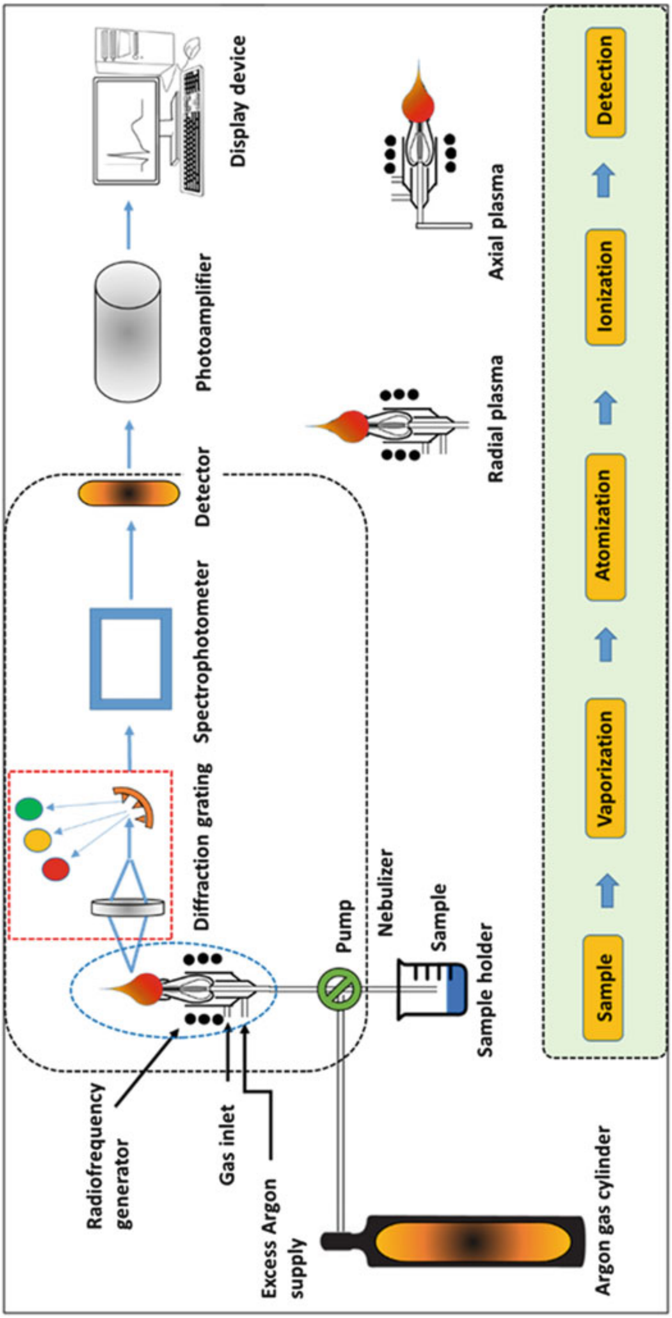

Fig. 10.2 Instrumentation and processes involved in inductively coupled plasma-optical emission spectrometry (ICP-OES)

time in Ar plasma as well as curtails cost of operation of each sample. Nevertheless, the sensitivity somehow reduces due to low consumption of Ar. Few studies have reported that determination of As, Ca, Cd, Co, Cu, Ni, Na, Mn, Mg, Zn, and Pb of microwave digested samples through conventional Fassel-type and modern bulb-shaped static high-sensitivity ICP-torch is comparable with each other (Engelhard et al. 2008; Nowak et al. 2014). In second approach, optical operation under sealed condition will result in recirculation of purge gas (pure Ar or N_2) through small purifier cartridge with no Ar or N_2 refill (Wheal and Palmer 2010; Hou et al. 2016; Donati et al. 2017).

- *Higher resolution*: Relatively low resolution of ICP-OES creates a problem in determination of elements like Np, Th, Pu, and Nd in nuclear fuels. Improving instrument resolution enhances background correction (Donati et al. 2017).
- *Dual view plasma operation*: Dual view plasma torch means axially configured plasma, which also allows for radial view through a hole in the side of axial torch (Fig. 10.1). Radial configuration allows robust analysis with minimal interference and used for metallurgy, petrochemical, etc., whereas the axial configuration has lowest limit of detection with the best sensitivity and used in pharmaceutical and environmental analysis (Donati et al. 2017).
- *Improved sample introduction and sample preparation*: Among recent advancement, improved ICP-OES mainly consists of pneumatic nebulizer, ultrasound nebulization, electrothermal vapourization, and temperature-controlled spray chambers (Hassler et al. 2016; Hosseinzadegan et al. 2016; Giersz and Jankowski 2016).

Støving et al. (2013) reported that quantitative determination of As, Cd, Cu, Cr, Fe, Hg, Ir, Mn, Mo, Ni, Os, Pb, Pd, Pt, Rh, Ru, V, and Zn in medicinal tablets could be precisely done by ICP-OES method.

10.6.3 Microwave Plasma-Atomic Emission Spectrometry

Microwave plasma-atomic emission spectrometry has identical physical properties of general plasma type and plasma used in ICP. Microwave plasma is produced from ionization of gaseous medium (Ar, He, Ne, He+O, O, and N) in the presence of electromagnetic microwave fields (usually 2.45 GHz) (Skogerboe and Coleman 1976). In MP-AES, production of plasma solely depends on ionization of gaseous medium due to electro-dynamic interactions and collision among electrons generated from applied electromagnetic field and gaseous atoms. In the absence of combustion process, microwave plasma initiated with electron seeding through 'Tesla discharge' and wide range of operation condition maintained through selection of collision frequency/gas pressure, gas flow, power of coupling condition, and microwave field potential (Vysetti et al. 2014). Microwave generation from magnetron and flame-like plasma at the tip of the coaxial conductive electrode is the characteristics of capacitively coupled system (CMP), whereas electrode-less system known as microwave-induced plasmas (MIP) (Skogerboe and Coleman 1976). The temperature of plasma (2300 to 8500 °C) depends on properties of support gas (Ar, He, Ne, He+O, O, and N), operating pressure (1.2 to 760 torr), and power level (25 to 600 W). Supporting gases like He, He+O, Ne, and N generally operate at lower operating pressure and produce lower plasma temperature. MIP type of plasma is more efficient than CMP type of plasma due to less operating pressure, power level, and more sensitive detection limit. Recent studies indicated that MP-AES with N supporting gas generates stable plasma at a lower cost than the ICP-OES (Jung et al. 2019). MP-AES generally operated at a lower temperature (4800 to 5000 °C) compared to ICP-OES (6000 to 8000 °C). Besides, presence of water vapour consequently appears to 'thermalize' the plasma, probably via a rotational coupling mechanism (Skogerboe and Coleman 1976). Fujihara and Nishimoto (2020) reported that hydride generation, along with MS-AES, has higher accuracy and precision in Sb determination with 0.05μg L^{-1} limit of detection and 0.15μg L^{-1} limit of quantification.

10.6.4 Inductively Coupled Plasma-Mass Spectrometry

ICP-MS is undoubtedly considered as one of the most advanced instrumentation in the quantitative elemental analysis even at ultra-trace levels and species wise. ICP-MS is a combined package of very high-temperature ICP of Ar and quadruple mass spectrometer (Houk et al. 1980). The high temperature of Ar in ICP vaporizes the sample and the vaporized sample is then converted to positively charged ions in a swift chain process; correspondingly, these ions are detected by mass spectrometer based on their mass/charge ratio (Houk et al. 1980; Balaram 1996; Ammann 2007). Detailed ICP-MS instrumentation, working principles, and the main difference between ICP-OES and ICP-MS are highlighted in Fig. 10.3. For elements with same charge or valence, the diffraction and detection through charged couple device (CCD) detector entirely depends on mass of the ion. Interestingly it is the most suitable quantitative analytical methods for isotopes. Through ICP-MS majority of elements of periodic tables can be determined at one part in 10^{15} levels (Balaram 2016). Rare earth elements and platinum group elements could also be successfully determined through ICP-MS. Recently conventional quadrupole mass spectrometer based ICP-MS further developed to ICP-tandem mass spectrometer or triple quadrupole ICP-MS (Fernández et al. 2012; Balcaen et al. 2013). Since the last 15 years, a combined effort of several research organization and companies modified the conventional quadrupole-based ICP-MS after equipped an extra quadrupole-, hexapole-, or octopole-containing cell (Balcaen et al. 2015). Robust comparison about the limits of detection of some elements among F-AAS, GF-AAS, CMP-MP-AES, MPI-MP-AES, ICP-OES, and ICP-MS is provided Table 10.4.

Sample preparation and caution took to deliver samples

- For better accuracy and precision in quantitative assessment, samples were prepared through microwave-assisted acid digestion either using 'aqua regia'

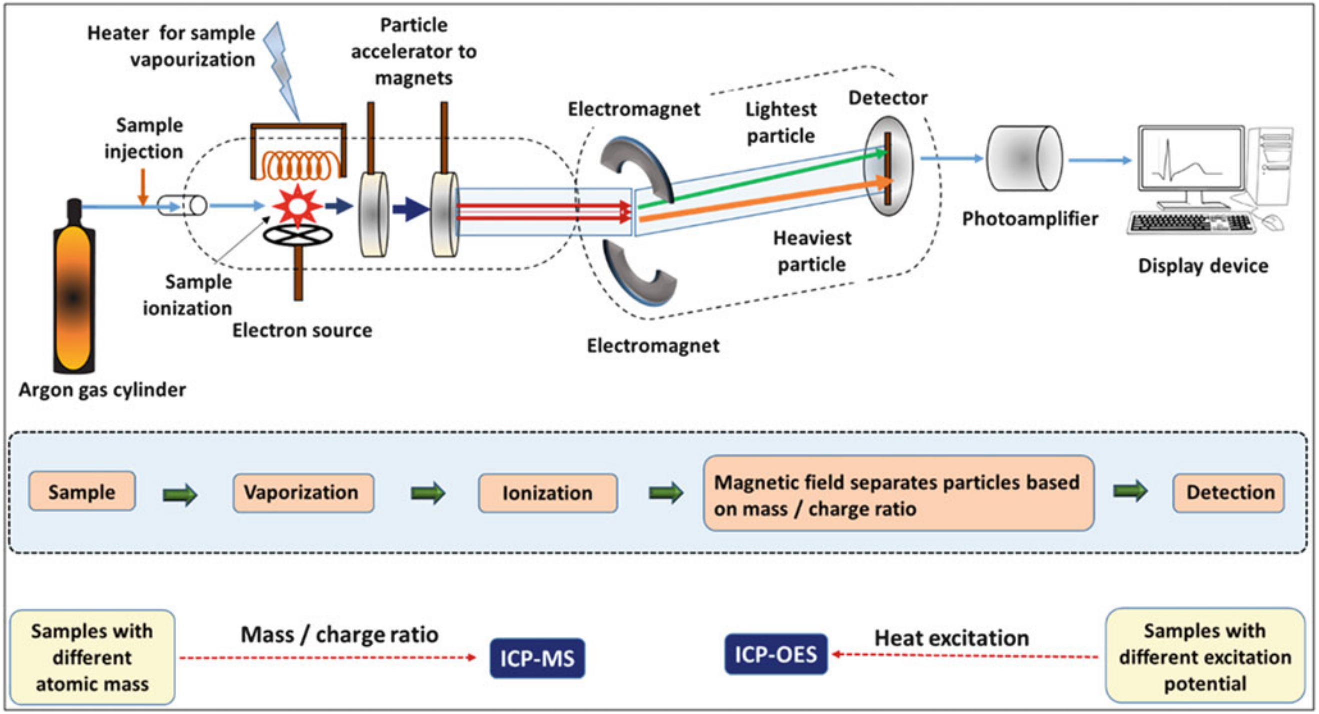

Fig. 10.3 Instrumentation, processes involved in inductively coupled plasma-mass spectrometry (ICP-MS) and the difference between the working principle of ICP-OES and ICP-MS

Table 10.4 Comparison of limits of detection (μg L^{-1}) among advanced spectrometry techniques for some elements

Elements	Instrumentation techniques					
	AAS		MP-AES			
	FAAS	GF-AAS	MIP	CMP	ICP-OES	ICP-MS
As	0.1	–	30	4000	0.04	–
Cd	1.0	0.02	0.4	500	0.07	0.003
Co	5.0	–	60	–	3.0	–
Cr	4.0	0.06	0.4	–	0.08	0.02
Cu	2.0	0.1	1.0	20	0.04	0.003
Al	30	0.2	0.6	20	0.2	0.06
Pb	5.0	0.2	1.0	200	1.0	0.007
Sn	15	10	–	–	1.0	0.02
Ca	1.0	0.5	0.05	–	0.0001	2.0
Mg	0.2	0.004	10	100	0.003	0.15
Mn	2.0	0.002	1.0	100	0.01	0.6
Fe	6.0	0.5	10	50	0.09	0.45
Zn	1.0	0.001	0.6	100	0.1	0.008
Ni	3.0	1.0	1.3	–	0.2	0.005
K	2.0	0.1	0.65	–	75	1.0
Na	0.2	0.004	0.12	–	0.1	0.05
V	25	2.0	80	50	8.0	0.005
Mo	5.0	1.0	1.5	–	0.2	0.003
P	50,000	–	33	–	30	0.1

Source: Data taken and compiled from Lichte and Skogerboe (1974), Boumans et al. (1975), Skogerboe and Coleman (1976), Welz (1985), Hou and Jones (2000), Balaram and Rao (2003), Skoog et al. (2007), Vysetti et al. (2014), Balaram (2016), Ferreira et al. (2018)

(a mixture of 63% HNO_3 and 37% HCl at 3:1, v/v) (Balaram 2016) and delivered in 12–15 mL tubes.

- Solid materials should be destructed before insertion in the instrument. The concentration of HNO_3 should be maintained below 10%, preferably 1% if necessary, perform excess microwave-assisted digestion.
- For keeping the metals in solution, samples should be acidified with 1–5% HNO_3.
- Use of HCl causes precipitation and sulphur in H_2SO_4 may cause spectral interference.
- Salt content should be checked and maintained below 2%, permissible up to 3% (30 gL^{-1}).
- Samples must be free of HF, which corrodes the instrument wall.
- ICP samples should be free from any organic solvents.

10.6.5 Ion selective electrodes

At a time, multiple ions may interfere with each other during activity detection. Particularly anion detection is problematic as most of the cations could easily be detected by using AAS and ICP-OES. An easy way of anionic quantification is through ICP-MS, but this did not yield suitable anionic activity measurement and also is too costly to perform at a routine scale. Thus, use of ion selective electrodes or specific ion electrode is the best alternative option to determine specific anionic activity in solution. Ion selective electrode is a sensor (or transducer) which converts ionic activity into electric potential following the Nernst equation (Bard and Faulkner 2001; Yue and Liang 2018). A typical ion selective electrode is made up of an ion-conducting membrane, internal solution of the interested ion, and a reference electrode (Jeffery et al. 1989). It should be assured that ion of interest should be mixed with the membrane material; the membrane is nonporous and insoluble to water. An ion selective electrode generally measures the potential difference between inner solution and outer solution of membrane (Yue and Liang 2018). Ion selective electrodes work on the basic principle of the galvanic cell. The net charge across the membrane is determined by comparing with reference electrode, whereas net charge is directly proportional to the activity of the selected ions (anions). Mathematically this could be described as follows:

$$E_{\text{cal}} = E_{\text{det}} - E_{\text{ref}}$$

where E_{cal} is calculated potential, E_{det} is detected potential, and E_{ref} is reference potential.

There are four different types of ion selective electrodes, namely glass electrode, solid state electrode, liquid state electrode, and compound electrode. Glass electrodes are either made up of silicate glass used for single charged ions or chalcogenide glass for double charged ions. The commonly used glass electrode is pH metre. Among solid state electrodes, crystallite electrodes are made up of mono- or poly-crystallites of interested ion (Buck and Lindner 1994; Bakker and Qin 2006). Fluoride (F^-) selective electrode is an example of a solid state ion selective electrode. The other two forms have limited use in soil research. The adoption of nitrate, chloride, and other anion specific electrodes has also been established to incorporate nitrogen, chlorine, and other anion estimations in multinutrient elemental extractability research. All these advanced instrumentations (Fig. 10.4) can be a cue to promulgate the research further.

10.7 Economic Prosperity for Advanced Soil Elemental Analysis

Traditional soil testing methods often consider the economy of the laboratory but disregard the farm level economy that can be achieved by more precision in diagnosis of nutrient deficiencies (Raij 1998). Reliability, consistency, correlatability, and reproducibility are the prime hardship for routine and existing

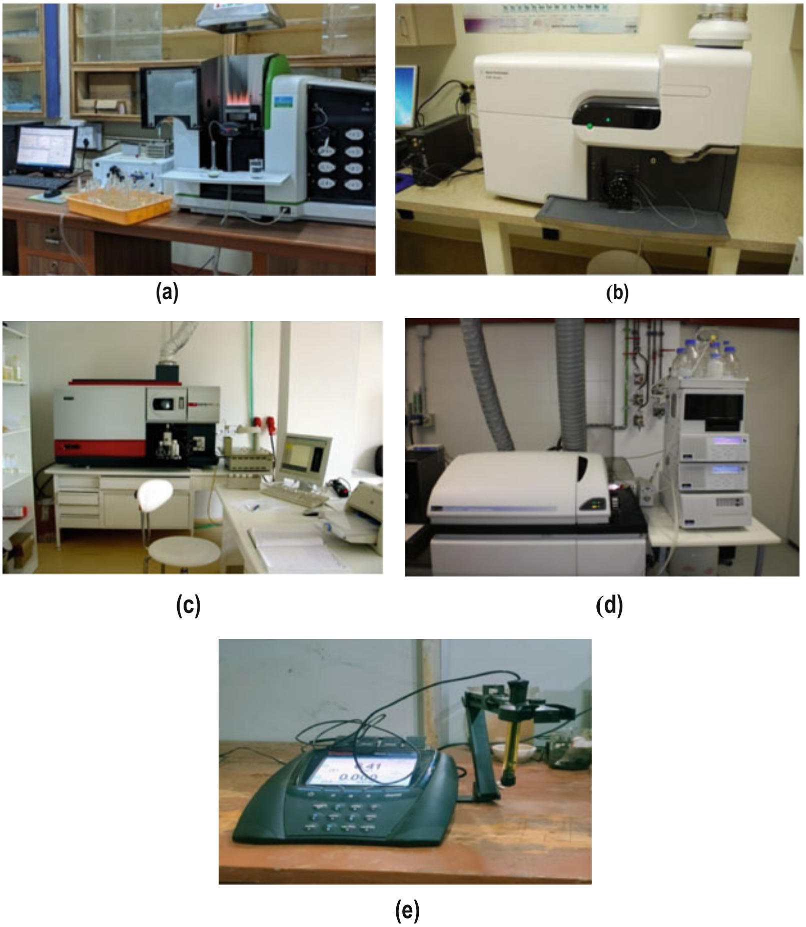

Fig. 10.4 Advanced instrumental setup for augmenting soil–plant nutrition research. (**a**) Atomic absorption spectrophotometer, (**b**) Microwave plasma-atomic emission spectrophotometer, (**c**) ICP-optical emission spectrophotometer, (**d**) HPLC mediated ICP-mass spectrophotometer, (**e**) Ion specific electrodes

soil analytics and testing cost is also under the influence of enormous spatio-temporal variabilities. In northern American region, it costs $ 6–95, whereas in Africa it fluctuates within $ 20–45 and often requires prolonged waiting times for results generation (Dimkpa et al. 2017). Globally multinutrient soil extraction process and advanced diagnostic techniques would be an expedite option even to the laboratories which are encountering by shortage of hard currency fetched chemicals and laboratory supplies (Mamo et al. 1996) by rapid, simple, and accurate nutrient testing mechanism. With the validated multi extractant method and accuracy, ICP-OES and ICP-MS can measure multiple elements from numbers of samples in a single analytical run with a short time span; however, generally, it demands prerequisite training and infrastructure to perform well. So far assessing extractant suitability for soil test, economics have not been considered seriously but for exhaustive and reliable testing service, their cost and convenience must be relooked or compared especially in third world countries where monumental sample size and inadequate budgetary provision are complicating the analytical service. For instance, AB-DTPA and AAAc-EDTA multinutrient extractant have been found to be more accurate and economical in the soil of Himachal Pradesh, India, where it costs Rs. 703 and Rs. 1483, respectively, in comparison to Rs. 1989 by conventional reagents for 1000 samples, excluding other common costs (Sharma et al. 2018). Establishment of a soil–crop specific field calibration data for a new testing process and conversion factor between new and current one for value interpretation are useful and serve interim measures for most soil testing laboratories for simultaneous estimation using a single extractant (Sims 1989).

10.8 Interpretation and Validation of Multinutrient Research Findings

10.8.1 Significance of Critical Soil Nutrient Concentration Under Elemental Extraction Procedures

Soil testing serves the purpose of considering only a fraction of the total soil nutrient concentration which correlates with plant yield/uptake. Soil test analytical data are expounded to characterize the soil nutrient status and vary widely depending on the different elemental extraction processes including chemical concentration and the soil-extractant reaction time. Comparative efficiency among different extractants is measured about calibration with plant response indices by doing greenhouse and/or field trial experiment with different graded doses of fertilizer under a specific soil-crop-regional climate setup. For a smooth calibration, relationship among soil test data by a procedure and the crop response to the added nutrient must be established. It is advisable to have a set of wide range of soil test result which includes deficient, optimum, and above-optimum values to represent a broad spatial region on which crop yield response is appraised (Mallarino 2005). The purpose is to point out the specific soil test value (critical concentration limit) below which plant growth is impeded and significant fertilizer responses to applied fertilizer are found. It is utmost essential to formulate the critical concentration of available nutrients by different extractants. The critical limits of nutrients in soils are computed through plotting soil test values (X-axis) against Bray per cent yield (BPY) (Y-axis), and the critical limits of grain–nutrient concentration are quantified through plotting grain–nutrient concentration (X-axis) against BPY (Y-axis) (Cate and Nelson 1965); here BPY is calculated by the formula as follows: (yield without nutrient/yield with optimum nutrient)*100 (Saha et al. 2018a). In another way, the critical limit may be estimated by following the statistical method (Cate and Nelson 1971). Establishment of critical concentrations of plant-available nutrients in soil is efficacious for early stage detection of nutritional deficiency to crop to recommend adequate measures before crop sowing/transplanting. However, the critical limit is very much influenced by numerous factors related to the soil properties and crop nutrient requirement as well as the chemical behaviour of extractant used. Thus critical limit for a soil nutrient and soil extractant must be investigated for successful fertilizer recommendations by involving all set of smooth soil test calibration and accurate soil test interpretations where soil nutrient status and soil–plant characteristics are the input variables.

Till now, in countries like India, background research for the choice of critical values with routine soil test procedure consisted of a few pot culture and field experiments with paddy and wheat which has been extensively used for generalized fertilizer recommendations for a couple of decades (Dey 2015) which neglect the soil–crop specificity and may over/underestimated the actual need for a crop. There exists a wide global variation in extraction with chemical reagents, testing instrumentations; calibration processes jeopardize the overall fertilizer prescriptions for a reference. For the last few decades, multinutrient soil extraction study is getting confidence for routine soil analysis by using advanced multi-element analysers for assaying prepared soil extract (Bibiso et al. 2015) for its reliability, accuracy, and precision. Therefore, research for such critical limits of P, K, S, Zn, and B in soils for deficiency of various crops by using multinutrient extractant was started by different researchers around the globe and few of them has been compiled in this chapter (Table 10.5). These values for each nutrient differ with soil, agro-climatic region, crop, and nature of extractant used. So, more precise priorities must be weighted towards individual critical soil nutrient concentration along with extractant study.

10.8.2 State of Soil MultiNutrient Extractants Research and its Global Scenario

Soil testing supervises and generates a framework and basis for successful, effective fertilizer recommendation by working out nutrient supplying power to the standing crop from the existing soil under the prevailing agro-climatic region. Thereof, various chemical extraction methodology used for assessing bioavailable soil nutrient heavily depends on nature of crops growth and their nutrient uptake pattern along with a broad range of soil characteristics, such as soil texture and mineralogy, soil organic carbon, soil pH and CEC, oxides and hydroxides of Al, Fe, and Mn (Lindsay and Cox 1985). So assessment of various extractant methodologies and their wet chemistry needs to be reviewed time to time under various soil-crop-regional scales and compared with soil properties, existing analytical methods, and finally with specific crop response for its accuracy and broader applicability. For the last five decades, several multinutrients are attaining confidence and have been tested globally for its soil and crop specificity to include in routine soil testing service. Some previous works in several countries furnish essential information about their location-soil-crop specificity, interrelationship with plant indices, and suitability over other chemical soil extractants although they are in scanty in numbers. In the current sections, the results for these purposes are reviewed, compiled, and

Table 10.5 A global compilation on soil–plant-nutrient mediated soil multinutrient extractant superiority

S. No.	Best extractant	Notable findings (Efficacy over others/ critical limits in soil)	Element extracted	Crop	Soil and Region	Location (country)	References	Extractants used
1	0.4 M CH_3COOH for acid soils, and EDTA/$(NH4)_2CO_3$ alkaline soils	$r = 0.88$ for 0.4 M CH_3COOH (interrelationship with plant indices)	Mn	Neubauer biotest	Chernozem, pseudogley, and humogley soils	Croatia	Bertie et al. 1997	14 extractants covering all existing methodology were tested
2	Hunter's procedure of P extraction	Critical level of P for Hunter, Olsen, Bray, Truog, and Nelson extractant was 12.5,14.5125,22.5,22.5 ppm	P	Wheat (*Triticum aestivum*)	16 top soils (0–15 cm) from different diverse soil series	Bangladesh	Ali et al. 1997	Hunter, Olsen, Bray, Truog, and Nelson extraction methods
3	AB-DTPA	Critical Mn level of 0.4 ppm was determined	Mn	Soybean (*Glycine max* cv.' Ransom')	2 adjacent field experiments near Tifton, Georgia	USA	Shuman et al. 1980	AB-DTPA, DTPA, NH_4CI-NH_4F, and HCI-H_2S0_4
4	0.1 N HCI	Critical levels of Zn for DTPA+$CaCl_2$, EDTA-$(NH_4)_2OAc$, EDTA-$(NH_4)_2CO_3$ and 0.1 N HCl were 0.48, 0.80,0.78, and 2.2 ppm	Zn	Green Gram (*Vigna radiata*)	22 non-calcareous soils from different locations	India	Gupta and Mittal 1981	1 N HCl,0.1 N HCl, EDTA-$(NH_4)_2CO_3$, EDTA-$(NH_4)_2OAc$, DTPA+$CaCl_2$, 1 M $MgCI_2$
5	AAAc-EDTA 1.0 M acidified ammonium acetate and 0.02 M EDTA; pH 4.65	Zn Deficiency < 1.0–1.5; Excess > 20–30 Cu < 0.8–1.0 (deficiency), >17–25 (excess)	Zn and Cu	Wheat (*Triticum aestivum*) and Maize (*Zea mays L.*)	8000 soil and plant samples	Broad range of soils over 30 tropical countries	Sillanpaa 1982	AAAc-EDTA, Fe DTPA, hot water, OA-AO
	Hot water extraction	Deficiency < 0.3–0.5; Excess > 3–5	B					

6	EDTA	$R^2 = 0.67$ and 0.40 for Zn and Cu by including (pH + organic matter + texture) (interrelationship with plant indices)	Zn and Cu	Oats (*Avena sativa*, cv. Lodi)	28 diverse groups of soils from western Nigeria.	Nigeria	Osiname et al. 1973	DTPA, 0.1 N HCl, 1 N HCl, EDTA
7	DTPA	The DTPA extractant showed the critical level of zinc—1.4 ppm	Zn	Maize (*Zea mays L.*)	30 calcareous soils	India	Singh et al. 1977	DTPA, 0.5 M KCl, 0.02 M EDTA, 1 N $(NH_4)_2OAc$; pH 4.8, 1 N $(NH_4)_2OAc$; pH 7.0 + 0.2% hydroquinone
8	0.05 M HCl	The critical limit for soil Zn and Cu was 1.0 ppm and 0.1 ppm	Zn and Cu	Rice (*Oryza sativa*)	33 diverse wetland flooded rice soils	South-east Asia	Ponnamperuma et al. 1981	0.05 M HCl, 0.1 M HCl, EDTA, and DTPA
9	$NaHCO_3$ and AB-DTPA	$R^2 = 0.74$ and 0.73 for $NaHCO_3$ and AB-DTPA with uptake	P	Corn (*Zea mays L.*).	88 Ontario soils (pH 5.0 to 7.6 and OC 60 to 575 g kg^{-1})	Central Canada	Bates 1990	$NaHCO_3$, AB-DTPA, Bray-Kurtz P1, Bray-Kurtz P2, and Mehlich 3
10	DTPA	$R^2 = 0.77$, 0.77, 0.66, 0.77 for wheat and 0.79, 0.90, 0.67, 0.79 for bean, respectively	Cu, Zn, Fe, and Mn	Wheat (*Triticum aestivum*) and Bean (*Phaseolus vulgaris*)	Soils from the 12 distinct locations of State of Paraná	Brazil	Sarto et al. 2011	0.1 M HCl, Mehlich-1, Mehlich-3, and DTPA
11	NH_4-acetate	$r = 0.82$,0.76, and 0.64 for K, Mn, and B	K, Mg, P, Mn and B	Spring Barley cv. Akcent	36 top soils from fields in 22 localities	Czech Republic	Matula 2009	Mehlich 3, ammonium acetate, 1:5 water extraction

(continued)

Table 10.5 (continued)

S. No.	Best extractant	Notable findings (Efficacy over others/ critical limits in soil)	Element extracted	Crop	Soil and Region	Location (country)	References	Extractants used
12	AB-DTPA (1:2 soil-extractant)	$r = 0.85$, 0.79, 0.86, 0.66, 0.72, 0.74 for P, K, Na, Zn, Mn, and Fe, respectively	P, K, Na, Ca, Mg, Zn, Cu, Fe, and Mn	Rice (*Oryza sativa)*	Diverse range of lowland rice soils	Sri Lanka	Madurapperuma and Kumaragamage 2008	1:2 and 1:4 AB-DTPA; conventional Olsen, Bray 1, FeO (P); neutral NH_4OAc (Ca, Na, K, Mg); DTPA (Zn, Cu, Fe, Mn)
13	Mehlich 3	$r = 0.97$,0.91 for Zn, Cu (Mehlich 3–0.1 M HCl)	Zn, Cu	Soil based (non-crop specific)	12 long-term experimental sites covering 7 agro-ecological zones	India	Pradhan et al. 2015	AB-DTPA, Mehlich 3 and 0.1 M HCl
14	Mehlich 3 and EDTA-NH_4OAc	For Mehlich 3 $R^2 = 0.97$, 0.88 for P and Zn. With EDTA-NH_4Oac, $R^2 = 0.86$,0.99,0.88 for Ca, Mg, and Zn	P, K, Ca, Mg, Cu, Zn, and Fe	Soil based (non-crop specific)	80 samples from acid soils from Galicia	Spain	Rodriguez-Suarez et al. 2007	EDTA-NH_4OAc, AB-DTPA, Mehlich 3, Bray 2, and ammonium acetate
15	0.374 M Na_2SO_4 and 0.45 M $NaHCO_3$ buffered at pH 8.5	$R^2 = 0.9033$–0.9326 for all three nutrients	N, P, and K	Corn (*Zea mays L.*).	Neutral and calcareous soils from Henan Province	Central China	Ma et al. 2020	0.45 M $NaHCO_3$ + 0.374 M Na_2SO_4 compared with standard protocols
16	AB-DTPA	Highest correlation was between AB-DTPA and DTPA ranging 0.85–0.99 for the selected micronutrients	Zn, Cu, Fe, and Mn	Soil based (non-crop specific)	7 representative acidic and basic soils (pH range 4.5–8.4)	Selected parts of Ethiopia	Bibiso et al. 2015	DTPA, 0.026 M EDTA, 0.01 M $CaCl_2$, 0.02 M $SrCl_2$, 0.01 M $BaCl_2$, 0.1 M $BaCl_2$, Mehlich 3 and AB-DTPA

17	Mehlich-3	Critical limit of Mehlich-3-extractable K, P, Zn, B and S for rice-51.2, 14.7, 1.27, 0.65, and 22.9 ppm	K, P, Zn, B, and S	Rice (*Oryza sativa)*	20 inceptisol and 20 alfisol soils with series level variation	Sub-Tropical India, West Bengal	Seth et al. 2018	DTPA, AB-DTPA, Mehlich-3, Modified Morgan, CDTA
18	DTPA and HEDTA at pH 5.3	$R^2 > 0.85$ for DTPA HEDTA (5.3) and DTPA (7.3)	Zn, Fe, Cu, Mn, Al, Cd, Ni	Soil based (non-crop specific)	25 diverse soil group including 12 agricultural soils	USA	Norvell 1984	DTPA, EDTA, HEDTA, EGTA and NTA. 0.005 M each +0.1 M $CaCl_2$ + 0.1 M HCl, NH_4OAc, and DTPA
19	0.01 M $CaCl_2$	$R^2 > 0.90$ for all three nutrients	Ca, Mg, and K	Soil based (non-crop specific)	39 widely varied agricultural soils	Netherlands	Van Erp 2002	0.01 M & 0.0125 M $CaCl_2$, 0.5 M NaCl, 1 M KCl, Mehlich-3, 0.1 M $BaCl_2$
20	0.01 M $CaCl_2$	$R^2 > 0.86$ for all three nutrients	Cd, Cu, Pb	Wheat (*Triticum aestivum)*	Widely varied nine soil series	Taiwan	Lee and Zheng 1994.	0.1 M HCl, 0.01 M $CaCl_2$, DTPA (5.3 and 7.3 pH)
21	Mehlich 1	$r > 0.91$ (M-1 vs M-3 for P), >0.96 (M-1 vs KCl for Mg), >79 (M-1 vs HCl for Zn, Cu)	K, P, Mg, Ca, Zn, and Cu	Soil based (non-crop specific)	441 soils from Rio Grande do Sul state	Brazil	Bortolon and Gianello 2010	Mehlich 1 (M-1), Mehlich-3,1 M KCl, 0.1 M HCl
22	0.1 M $BaCl_2$	$R^2 = 0.979$	K, Al, Ca, Mg, Na, and Mn	Rubber plant	Soils from 14 different rubber plantation sites from Kerala state	India	Rao 2005	1 N ammonium acetate, 1 M KCl, DTPA, and 0.1 M $BaCl_2$
23.	Mehlich-3	$R^2 = 0.73–0.86$ and non-significant for Na (0.51)	Mg, P, K, Ca, and Na	Soil based (non-crop specific)	22 Ethiopian and 10 German diverse soils were used	Ethiopia and Germany	Mamo et al. 1996	Olsen, 1 N NH_4OAc, Mehlich 1, Mehlich 3, calcium acetate lactate

(continued)

Table 10.5 (continued)

S. No.	Best extractant	Notable findings (Efficacy over others/ critical limits in soil)	Element extracted	Crop	Soil and Region	Location (country)	References	Extractants used
24	Mehlich-3	$R^2 = 0.67–0.98$ for all nutrients	P, K, Ca Mg, Zn, Co, Cu, Fe, Mn, Mo, Na, S, and B	Soil based (non-crop specific)	173 representative chemically fertilized surface soil	Australia	Walton and Allen 2004	Mehlich-3 comparison with 1 M NH_4Cl, DTPA, Colwell test for P, $NaHCO_3$ for K, 0.01 M $CaCl_2$ for B, and 0.25 M KCl for S
25	Kelowna extractant (0.25 N HOAc + 0.015 N NH_4F)	$r = 0.98$ and 0.97 for K and Na	K and Na	Soil based (non-crop specific)	100 diverse Canadian soils which represent 2 groups equally of pH 4.1–6.9 and pH 7–9.6	Canada	Van Lierop and Gough 1989	Kelowna, KEDTA (Kelowna + 0.001 M EDTA), KDTPA (Kelowna + 0.005 M DTPA), AAEDTA(0.25 N HOAc + 0.001 M EDTA), and AADTPA (0.25 N HOAc + 0.005 M DTPA)
26	Mehlich-3 and 0.2 M sodium tetraphenyl borate ($NaTPB_4$) method	$R^2 = 0.71$ and 0.74 for Mehlich-3 and 0.2 M sodium tetraphenyl borate ($NaTPB_4$) method, respectively, with plant K uptake	K	Winter broccoli (*Brassica oleracea*)	Wide soil fertility gradient and nutrient management options in Aeric Haplaquept	India	Dasgupta et al. 2016	AB-DTPA, 1 N NH_4OAc, Kelowna, Mehlich-3, 0.01 M $CaCl_2$' and 0.2 M $NaTPB_4$

27	0.1 N HCl	Critical limits for Zn, Cu, Mn, and Fe are 1–1.5, 2–3, 1–4, and 0.3–0.5 ppm, respectively	Zn, Cu, Mn, and Fe	Crop uptake/field soil samples analyses for vegetables, forage crops, and coconut	Representative soil and plant samples were analysed from various parts of the country	Jamaica, South America	Lindsay and Cox 1985	Few numbers of extractants were tested including routinely used by soil testing laboratories
	$NaHCO_3$ + 0.01 M EDTA + Superfloc 127, pH 8.5 1/10 (w/v)	Critical limits for Zn, Cu, Mn, and Fe are 3, 1, 5, and 10 ppm, respectively				Bolivia, South America		

summarized for each experiment in Table 10.5. The aim is not only to furnish a comprehensive overview of the proven methods but to present a section of the best-suited ones and to frame their compatibility across the countries.

However, among numerous multinutrient extractants, only a few of them have been experimented to prove its superiority over routine testing across a broad range of soil, crop, or countries towards nutrient management strategies so far. In reality, only a very few have any fairly independent validation as corroborated by the previous scientific literature. The compiled data reveals that most of best-suited extractants for multinutrients have been tested so far for alternative capabilities in a few countries of Europe, North America, and individual pockets of Asia. Whereas substandard, expensive, and time-consuming methods are still dominant in most of tropics and sub-tropics and injudicious soil nutrient assessment is still in vogue for most of the poor farmers. Nevertheless, several extractants have been successful in being alternatives for routine soil testing, but no single extractant has been established to be excellent under all conditions. The chelates and dilute acids with different compositions are found to be superior in this line. In most of the cases, the inclusion of soil properties has improved the calibration result with plant indices/ response for better interpretation under suitability studies, although the extensive databases are missing for its broader applicability across the soil types.

Further, it is realizable that most of the experiments are based on pot experiment or greenhouse study with a limited number and types of soils and is with lack of simulation and calibration under crop field situations. Besides that, minimal numbers of field crops have been taken into account for a region. In very few cases, critical concentration of best-suited extractants has been evaluated for a crop and soil type for nutrient deficiency management purpose. Therefore, all these gaps in scientific shreds of evidence need to be relooked for consideration of more remarkable universality for an extractant. Unfortunately, these factors and constraints are very much regulated by spatio-temporal variabilities which entangle the overall accuracy and precision for any suggested methodology (Dimkpa et al. 2017).

10.8.3 Future Line of Research

Successful soil testing service in most of the countries depends on regional levels calibration, interpretation of soil tests with field trials. Recent advanced instrumentation progress with ICP-MS, ICP-OES for multi-element analysis at a time may further explore the possibilities with alternative rapid testing methods (Mikkelsen et al. 2020). It is assertive to find out the best-suited alternatives through crop response study with their critical concentration limits and validation for a broader region. The result must be compared to ensure an acceptable level of agreement and also needs to be correlated and calibrated along with individual nutrient wise conventional testing results and important soil properties like SOM, clay content, etc. This validated calibration data may then be widely useful for networking fertilizer recommendation programme even by the routine soil extractant users. In this outlook, future investigation is requisite on methods calibration based on advanced modelling and state-of-the-art soil analysis techniques for relating spectroscopic outputs with nutrient bioavailability with multi-element analysis (Dimkpa et al. 2017).

10.9 Conclusion

In the purview of global food security, agricultural productivity augmentation is a primary necessity. The major challenge in the process of vertical expansion of productivity is the continuously emanating soil degradation. A large number of soils in different areas of the world are losing their productivity owing to a downward spiralling of fertility and upsurge of heavy metal pollution. The paramount emphasis is to be rendered to soil analysis to address the issue, as without the a priori knowledge of nutrient status of the soil no ameliorative measures can be sought for. The glitch in a huge load of soil testing with a limited workforce is facing the crunch of a short timed extraction and analytical procedure. The use of the universal multinutrient soil extractant as elucidated in this chapter can thus be a significant cue in economizing the process and robustly effectuating soil testing facilities for directly serving the farming community and indirectly acting as the powerful ammunition to fight the imbalanced nutrition conundrum in the whole world.

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Role of Biochar on Greenhouse Gas Emissions and Carbon Sequestration in Soil: Opportunities for Mitigating Climate Change

11

T. J. Purakayastha, Debarati Bhaduri, and Pooja Singh

Abstract

Biochar, a pyrolyzed product of biomass, is richer in aromatic carbon (C) and poorer in oxygen which provides structural recalcitrance to it against microbial decomposition in soil. Biochar, being a stable source of C when applied to soil, remains there for longer period of time imparting long-term soil C sequestration. This sequestering effect of biochar has another advantage to mitigate climate change by reducing emission of greenhouse gases (GHGs) from soil. Both the interconnected processes imparted by biochar have its prominent role in climate resilience and environmental sustainability. Researchers around the world have been focusing on this aspect; thus revealing new facts and findings on managing biochar in agriculture. In this chapter, an attempt has been made to describe the biochar-governed mechanisms on emission of GHGs from soil, how the structural and functional properties of biochar regulates that, and the other associated factors like feedstock type and pyrolysis temperature during biochar preparation and soil inherent properties controlling various processes. Similarly, highlights of C sequestration potential of biochar made up of different crop/animal residues and other regulating factors have been described. Increase in pyrolysis temperature and switching over from manure to wood as a feedstock for biochar production increase the stability of biochar and reduce emission of GHGs from soil. The

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soils low in organic matter trigger C mineralization than that with high organic matter content. Biochar in presence of N fertilizer is reported to enhance CH_4 sink/decrease source strength of soil. The strongest effect of biochar on enhancing C sequestration and reducing GHGs emission is evident when it is applied in acid soils than alkaline soils. Both the concurrent processes of C sequestration and GHGs emission bring sanity to soil by physically more stable, enriching soil fertility, biologically more active and resulting to enhanced soil quality and lowering the C-footprint in agroecosystems.

Keywords

Crop residues · Bio(active)-char · Pyrolysis · Soil-biochar interactions · Feedstock type · GHGs emission · Stability of biochar

11.1 Introduction

Anthropogenic greenhouse gas (GHG) emissions have increased since the pre-industrial era, driven largely by economic and population growth and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) that are unprecedented in at least the last 800,000 years (Mastrandrea et al. 2010). The concentration of CO_2, CH_4 and N_2O in the atmosphere since industrial revolution increased by 41.2%, 152–170% 20–20.7%, respectively due to anthropogenic activities (Blasing 2013). Total CO_2 emissions from fossil fuels and industry rose by 1.6% in 2018 to 37.1 Gt CO_2 (Kelly 2018). Climate change will amplify existing risks and create new risks for natural and human systems.

Agricultural lands occupy about 40–50% of the Earth's land surface which accounted for an estimated emission of 51 to 61 Gt CO_2-eq yr^{-1}(10–12% of total global anthropogenic emissions of GHG). The world population is expected to approach 10 billion people by 2050. With this projected increase in population and shifts to higher-meat diets, agriculture alone could account for the majority of the emissions budget for limiting global warming below 2 °C (3.6 °F) (Waite and Vennard 2018). This level of agricultural emissions would render the goal of keeping warming below 1.5 °C (2.7 °F) impossible.

Of global anthropogenic emissions, agriculture accounts for about 60% of N_2O and about 50% of CH_4. N_2O emissions from soils and CH_4 from enteric fermentation constitute the largest sources, 38% and 32% of total non-CO_2 emissions from agriculture in 2005, respectively (US-EPA: 2006). Biomass burning (12%), rice production (11%) and manure management (7%) account for the rest. Human-induced warming reached approximately 1 °C (likely between 0.8 °C and 1.2 °C) above pre-industrial levels in 2017, increasing at 0.2 °C (likely between 0.1 °C and 0.3 °C) per decade (Allen et al. 2018). Limiting warming to 1.5 °C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly CH_4 (Rogelj et al. 2018).

Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change. Substantial emissions reductions over the next few decades can reduce climate risks in the twenty-first century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development. In order to achieve large reductions in GHG emissions, sequestering carbon (C) in the terrestrial sink is needed (Paustian et al. 2016). The major challenges before the agricultural scientists is how to mitigate climate change by employing various methods to reduce emissions of GHGs into atmosphere and capturing CO_2 from atmosphere to securely store in the above ground and below ground.

11.2 Climate Change Mitigation Options

Among the principal components of radiative forcing of climate change, CO_2 has the highest positive forcing leading to warming of climate. Carbon dioxide has the least global warming potential among the major GHGs (viz. N_2O-298, CH_4–25 and CO_2–1), due to its much higher concentration in the atmosphere; it is the major contributor towards global warming and climate change. There are a number of improved and innovative agricultural practices available for reducing GHGs emissions from agroecosystems (Fig. 11.1) (Lal 2011). The agricultural practices are broadly divided into reducing emissions and sequestering emissions. Under reducing emissions, soil management, water management and crop management are the options. The soil management includes conservation tillage, high soil biodiversity and higher aggregation; the water management includes reduce runoff losses, soil amendments, aerobic rice, etc.; the crop management includes genetically improved varieties, high crop biomass production with deep root system, recalcitrant residues, etc. Land use, farming systems and soil, water and crop management are the pathways under sequestering emissions. Conservation of soil, water and nutrient, increase in ecosystem C pool, multiple ecosystem are the important avenues; agroforestry, lay farming, cover cropping are the important options under farming system approach; under soil, water and crop management, conservation tillage, integrated nutrient management, fertigation, bio-film and soil amendments with biochar are important pathways under land use. Biochar is considered as one of the important strategies under sequestering emissions option.

11.3 What Is Biochar?

Biochar is made by heating any organic material, such as wood, straw or manure, in an oxygen limited or zero oxygen environment, which releases gases (called syngas) and liquids (called bio-oils) and yields a solid product, which if intended for use as a soil amendment, is named biochar (Fig. 11.2) (Lehmann et al. 2006; Shackley and Sohi 2010). There are many ways to prepare biochar and most widely used method is electrically operated biochar maker in presence of continuous purging of nitrogen

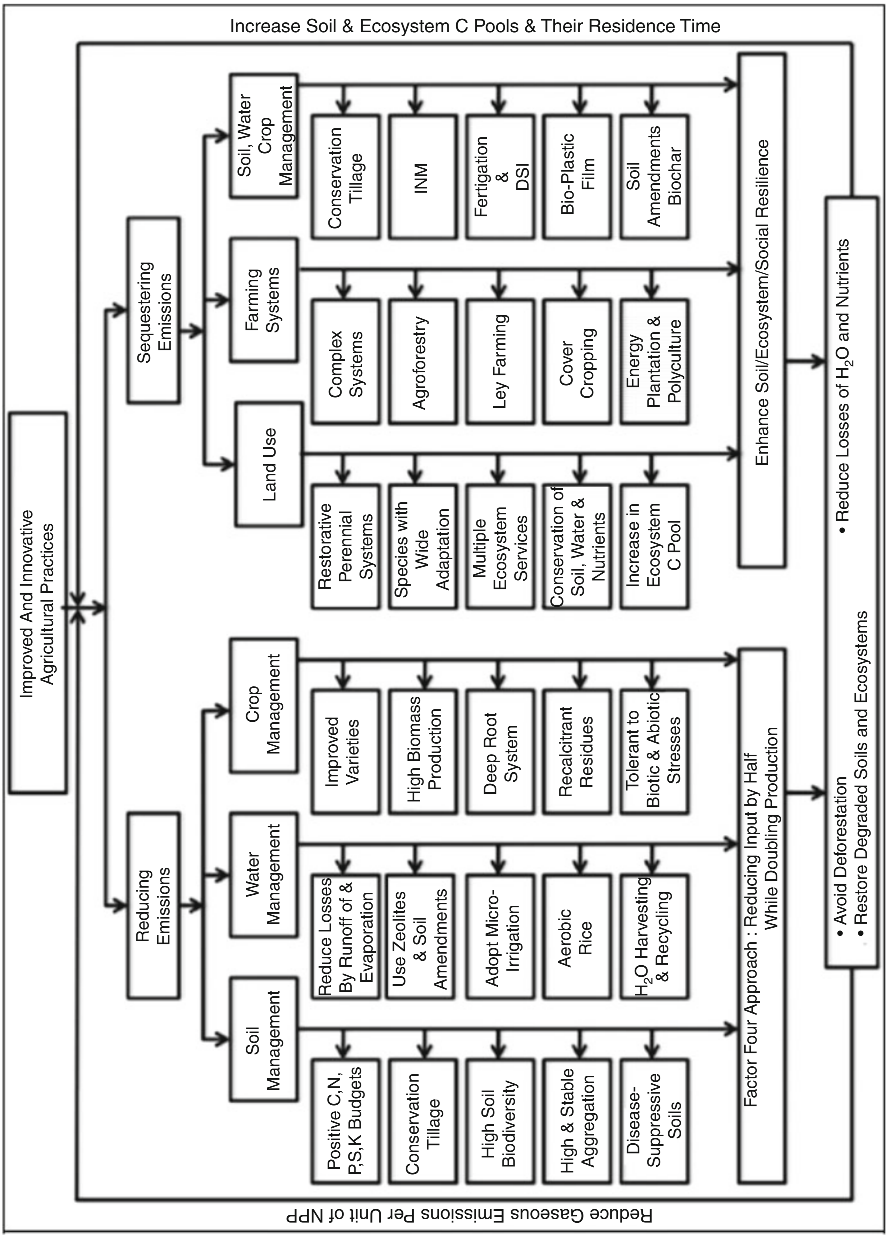


Fig. 11.1 Technological options to reducing emissions and sequestering emissions from agricultural ecosystems. *Source:* Lal (2011)

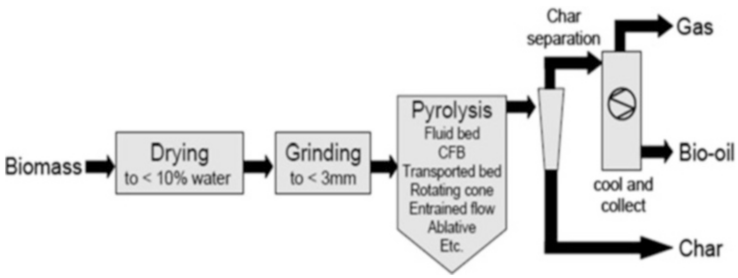


Fig. 11.2 Schematic diagram showing biochar production from biomass. *Source:* Sohi et al. (2009)

Fig. 11.3 Electrically operated temperature controlled biochar maker. *Source:* Purakayastha et al. (2016a)

gas (Fig. 11.3) (Purakayastha et al. 2016a). In contrast to the organic C-rich biochar, burning biomass in a fire creates ash, which mainly contains minerals such as calcium (Ca) or magnesium (Mg) and inorganic carbonates (Lehmann and Joseph 2009). The defining property is that the organic portion of biochar has a high C content, which mainly comprises the so-called aromatic compounds characterized by rings of six C atoms linked together without O or hydrogen (H), the otherwise more abundant atoms in living organic matter (Fig. 11.4). If these aromatic rings were

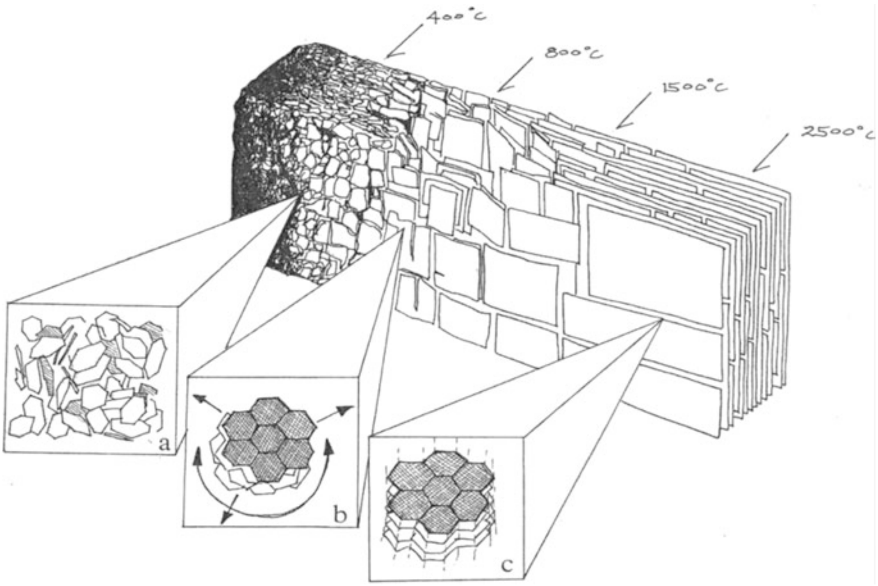


Fig. 11.4 Changes in structure of biochar with increase in pyrolysis temperature, (**a**) increased proportion of aromatic C, highly disordered in amorphous mass, (**b**) growing sheets of conjugated aromatic carbon, turbostratically arranged, (**c**) structure becomes graphitic with order in the third dimension. *Source:* Downie et al. (2012)

arranged in perfectly stacked and aligned sheets, this substance would be called as graphite. Under temperatures that are used for making biochar (<700 °C), graphite does not form to any significant extent.

11.4 Biochar to Mitigate Climate Change: Complex Mechanisms

The production and application of biochar—a C-rich material produced during the pyrolysis of biomass—to soil has been proposed as a means for mitigating anthropogenic GHG emissions (Lehmann et al. 2006). The Pyrolysis-Biochar Bioenergy Platform (PBBP) has the potential to mitigate GHG emissions through three principal pathways. First, bioenergy produced by PBBP will offset GHG emissions from the burning of fossil fuels and by converting photosynthetic biomass C into recalcitrant biochar C. Indeed, pyrolysis converts 10–50% of the original biomass C into biochar C, which persists in soils for hundreds to thousands of years (Lehmann et al. 2006; Lehmann 2007; Laird 2008; Roberts et al. 2010). Second, biochar amendments increase soil quality, potentially increasing net primary productivity and thereby reducing economic pressure to convert native lands to agricultural production (Kauffman et al. 2014). Third, soil biochar applications may directly reduce GHG emissions from soils.

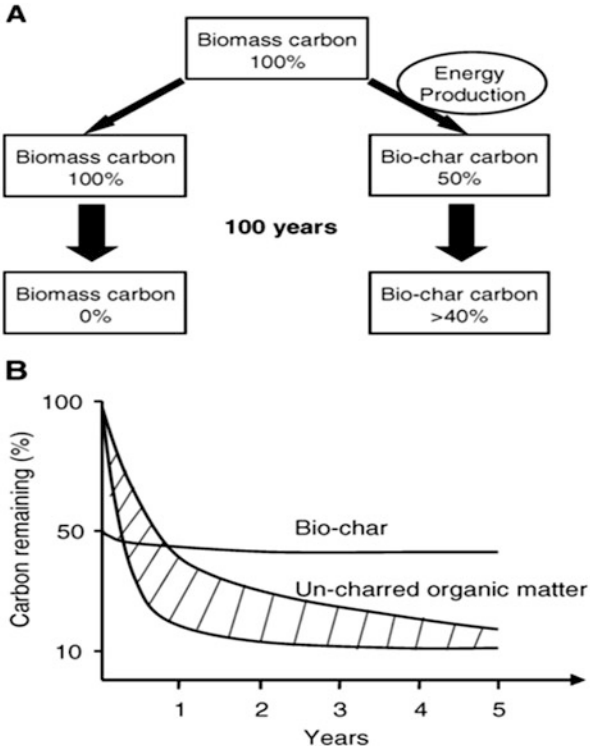


Fig. 11.5 Schematics for biomass or biochar remaining after charring and decomposition in soil. (**a**) C remaining from biomass decomposition after 100 years from IPCC (1996); (**b**) range of biomass C remaining after decomposition of crop residues from Jenkinson and Ayanaba (1977). *Source*: Lehmann et al. (2006)

Biochar found in high proportions in the so-called *Terra Preta* soils of the Amazon region (Liang et al. 2008) has been radiocarbon dated and found to originate from 500 up to 7000 years BC (Neves et al. 2004). Because of higher half-life, biochar is considered suitable for long-term C sequestration in soil. It was estimated the global C sequestration potential of C 0.16 Gt yr^{-1} as forest residues, mill residues, field crop residues and urban wastes is used for biochar production (Lehmann et al. 2006). Thus, biochar allows more C input as compared to the C output and this is the basis behind biochar's possible C negativity and hence its potential for climate change mitigation. It is possible to increase 25% of soil C as the biochar storage capacity of temperate grassland and cropland is about 400 Gt (Lehmann et al. 2006). The charred material releases 50% of the labile C into the atmosphere during its formation and remaining non-labile C remains into soil while non-biochar material application into soil releases C into the atmosphere (Lehmann et al. 2006) (Fig. 11.5).

Biochar being a pyrolyzed product is highly stable and resistant to decay by microorganisms. Thus there is considerable interest in the concept of applying biochar in to soil as a long-term sink for C, thereby mitigating climate change (Prayogo et al. 2014). In this connection, the application of biochar to soils has been shown to achieve the net C gain in soils while also serving for increased plant biomass production by enhancing the nutrient supply to plants and increasing nutrient and water use efficiencies (NUE and WUE) by plants (Kookana et al. 2011; Lehmann et al. 2006; Lehmann et al. 2015; Minasny et al. 2017; Purakayastha et al. 2015, 2016b, 2019) and decreased N_2O and CH_4 emission from soils (Rondon et al. 2005). Besides direct effects of biochar on nitrifying organisms, it is possible that biochar could induce strong N immobilization and could decrease ammonification and nitrification in the short term (Lehmann et al. 2006; Warnock et al. 2007). Mukherjee and Lal (2013) described the probable mechanism governing GHG flux of biochar-amended soils following 2-phase complex formation hypothesis. The initial flux of CO_2 from biochar-added soil is a result of microbial interaction of labile-C (volatile and short-duration compounds) of biochars in a weak complexation (non-specific EDA type interaction/H-bonding) with soil mineral surface. The second phase of GHG emission is not instant but gradually happened over a longer time and often slower in rate, as a consequence of relatively stable complex formation (cyclic aromatic compounds) within the inner core of biochar in interaction with soil mineral and microbial biomass.

Methane flux measured at the soil–atmosphere interface is the net effect of two processes: methane production by methanogens and methane uptake by methanotrophs (Dunfield et al. 1993). Biochar applications are expected to make soil conditions favourable for methanotrophs and unfavourable for methanogens, thereby increasing the CH_4 sink capacity of soil. The mechanisms by which biochar may affect soil CH_4 fluxes include sorption of CH_4 to biochar's surfaces (Yaghoubi et al. 2014) and soil aeration by biochar addition, which may increase diffusive CH_4 uptake (Van Zwieten et al. 2010; Karhu et al. 2011), as microbial CH_4 oxidation in upland soils is mostly substrate-limited (Castro et al. 1994).

Thus, biochar application to soils has been recommended as an important component of the pathway to "climate-smart" soil management practices in modern global agriculture (Paustian et al. 2016; Purakayastha et al. 2019). Therefore, biochar addition is a *win–win* strategy for climate change mitigation and enhancing crop production.

11.5 Biochar Stability: A Prerequisite for Carbon Sequestration in Soil

The composition changes through a complete destruction of cellulose and lignin and the appearance of aromatic structures (Paris et al. 2005) with furan-like (five-membered aromatic ring with four C atoms and one oxygen) compounds (Baldock and Smernik 2002) during pyrolysis have a significant effect on the stability of biochar. The following properties of biochar make it more stable in soil system.

11.6 Aromaticity

Biochar is commonly considered to be highly aromatic and containing random stacks of graphitic layers (Schmidt and Noack 2000). Purakayastha et al. (2015) conducted FTIR analysis and confirmed the functional groups present in maize stover biochar contributed significantly to the cation exchange properties (Fig. 11.6). In general, H/C and O/C ratios in experimentally produced biochars decrease with increasing temperature (Shindo 1991; Baldock and Smernik 2002; Purakayastha et al. 2016b) and increased with time of heating (Almendros et al. 2003).

11.7 Presence of Amorphous Structures and Turbostratic Crystallites

Biochar is mainly characterized by amorphous structures and turbostratic crystallites that may contain defect structures in the graphene sheets with oxygen (O) groups and free radicals (Bourke et al. 2007). Ordered graphene sheets were found to increase only at a carbonization temperature above 600 °C (Kercher and Nagle 2003). Because of their unordered structure, amorphous and turbostratic crystallites have a high stability (Paris et al. 2005), which could be one reason for the stability of biochar produced at relatively low temperatures of <600 °C.

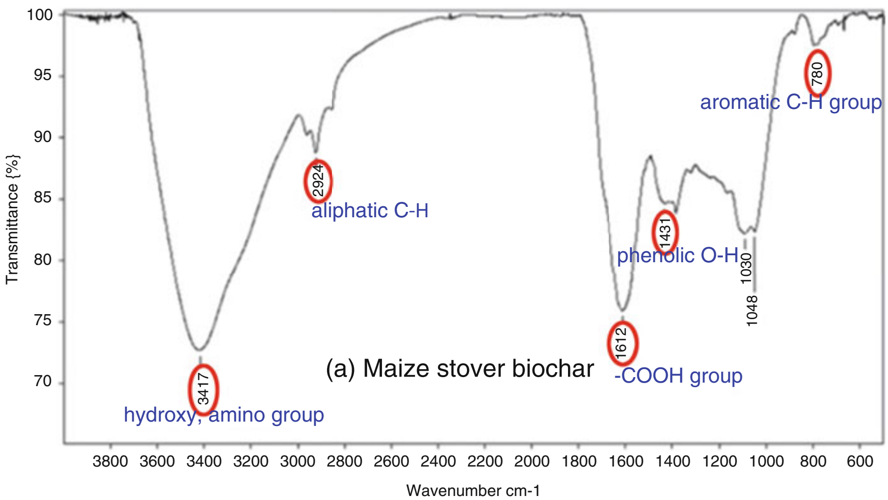


Fig. 11.6 Infra-red spectrogram of maize stover biochar. *Source*: Purakayastha et al. (2015)

11.8 Presence of Rounded Structures

Rounded structures may be even more stable than turbostratic structures in biochar (Cohen-Ofri et al. 2007). For cedar wood pyrolyzed at 700 °C, onion-like graphitic particles have been observed that are probably formed from lignin (Hata et al. 2000), but it is not clear whether these are a common feature in biochar (Shibuya et al. 1999). The round structures are actually fullerenes, molecular-scale spherical structures that include both hexagonal and pentagonal rings that have great stability (Harris 2005). Rounded features were also reported in biochars from German Chernozems with ages of 1160–5040 years using high-resolution transmission electron microscopy (Schmidt et al. 2002).

11.9 Reduced Accessibility to Decomposers

Biochar has been preferentially found in fractions of SOM that reside in aggregates rather than as free organic matter (Brodowski et al. 2006; Liang et al. 2008), which is considered to reduce its accessibility to decomposers. Biochar particles are, indeed, abundant within stable micro-aggregates. Moreover, microorganisms can be spatially associated with biochar in soils as porous structure of biochar invites microbial colonization. Reducing accessibility by aggregation is, therefore, proposed to be significant in controlling biochar decomposition, but of less importance than chemical recalcitrance.

11.10 Particulate Nature

The particulate form may have an important role in decreasing decomposition rates of biochar and increasing recalcitrance of biochar. Oxidation of biochar particles starts at its surfaces (Cheng et al. 2006) and typically remains restricted to the near-surface regions even for several millennia (Lehmann et al. 2005; Liang et al. 2006; Cohen-Ofri et al. 2007). Therefore, due to particulate nature, outer regions of a biochar particle protect the inner regions from access by microorganisms and their enzymes.

11.10.1 Interactions with Mineral Surfaces

A significant portion of biochar is found in the organo-mineral fraction of soil (Brodowski et al. 2006; Laird et al. 2010), suggesting that biochar forms interactions with minerals. Rapid association of biochar surfaces with Al and Si and, to a lesser extent, with Fe was found during the first decade after addition of biochar to soil (Nguyen et al. 2008). Coating of biochar particles with mineral domains is frequently visible in soils (Lehmann 2007) and suggests interactions between negatively charged biochar surfaces and either positive charge of variable-charge oxides by ligand exchange and anion exchange, or positive charges of phyllosilicates by cation bridging. Similarly, Ca was shown to increase biochar stability, most likely by enhancing interactions with mineral surfaces (Czimczik and Masiello 2007).

11.11 Role of Biochar on Soil C Sequestration

Soil C sequestration refers to capture of CO_2 from atmosphere and securely store into soil so that it is not immediately emitted into atmosphere. Plant biomass decomposes in a relatively short period of time, whereas biochar is orders of magnitudes more stable. So, given a certain amount of C that cycles annually through plants, half of it can be taken out of its natural cycle and sequestered in a much slower biochar cycle. By withdrawing organic C from the cycle of photosynthesis and decomposition, biochar sequestration directly removes carbon dioxide from the atmosphere and stores it in a much more durable form in soil. So, locking C up in soil makes more sense than storing it in plants and trees that eventually decompose (Lehmann 2007). The biochar C sequestration is influenced by various factors, e.g., feedstock type, pyrolysis temperature, soil properties, etc., which are described below.

11.11.1 Feedstock Type and Pyrolysis Temperature

The type of feedstock influences the efficiency of C conversion into the resultant biochar provided that the pyrolysis temperature for production is in the range of 350–500 °C (Lehmann et al. 2006). Any biomass material can be converted in to biochar but its yield and other physico-chemical properties vary (Verheijen et al. 2010). Baldock and Smernik (2002) showed that 20% of the added organic C from unaltered *Pinus resinosa* wood (heated at 70 °C) was mineralized, but, this value was $<2\%$ for samples heated at temperatures ≥ 200 °C indicating much higher stability of thermally altered woods. The greater stability of biochar prepared at higher temperature mainly due to the differences in proportion of alkyl and aromatic groups that increases with rise in temperature (Mcbeath and Smernik 2009).

Biochar prepared from wood pellets made from a mixture of Black Spruce (*Picea mariana*) and Jack Pine (*Pinus banksiana*), the solid fraction of pig manure and switchgrass (*Panicum virgatum* L.) at the highest pyrolysis temperature with low O/C_{org} and H/C_{org} ratios resulted in the lowest increase in CO_2 emissions, which could indicate a higher biochar C stability (Brassard et al. 2018). Wood biochar was most stable and pig manure biochar was least stable in silty loam and loamy sand soil; biochar prepared from switch grass was medium in stability (Brassard et al. 2018). Bruun et al. (2010) reported that mineralization of ^{14}C labelled biochar decreased considerably as production temperature increased from 400 °C to 500 °C, but reduced at 600 °C. The increased CO_2 evolution, in the early stages of experiment is derived from the carbonates of biochar, whereas at 600 °C the carbonate content is more in biochar showing less-induced mineralization.

Purakayastha et al. (2016b) reported that corn stover biochar prepared at 600 °C was more stable in Mollisol and Ultisol.

11.11.2 Application Rate of Biochar

The dose of biochar into soil is an important aspect to acquire C stabilization in soil. As Butnan et al. (2017) reported that application of biochar at 2% dose in soil helps in better stabilization over the 1% or 4% doses. In other study, application of rice husk biochar at a dose of 41.3 Mg ha^{-1} in Gleysol, Nitosols, Acrisol could increase 12.9, 12.4 and 0.51 kg of soil C with respect to control (Haefele et al. 2011). Similarly, the application of maize stalk and pinewood biochar at the rate of 10 Mg ha^{-1} and 5 Mg ha^{-1} in Nitosols could increase soil C by 0.77% and 0.71% in comparison to control (Nigussie et al. 2012). Purakayastha et al. (2015) reported that application of maize stover, pearl millet stalk, rice straw and wheat straw biochar at the rate of 20 Mg ha^{-1} enhanced total soil C by 65%, 52%, 41% and 64%, respectively, in an Inceptisol from Delhi (Fig. 11.7).

11.11.3 Soil pH

In general soil pH tends to increase on application of biochar. It was reported that on an average application of biochar at a dose of 20 or 40 Mg ha^{-1} tends to increase the soil pH by 0.2 or 0.4 units in a loam acidic soils with pH 6.0 (Liua et al. 2019). It was reported that poultry litter biochar is highly alkaline in nature, hence significantly affect the pH of the acidic soils (Purakayastha et al. 2019). In the alkaline soils

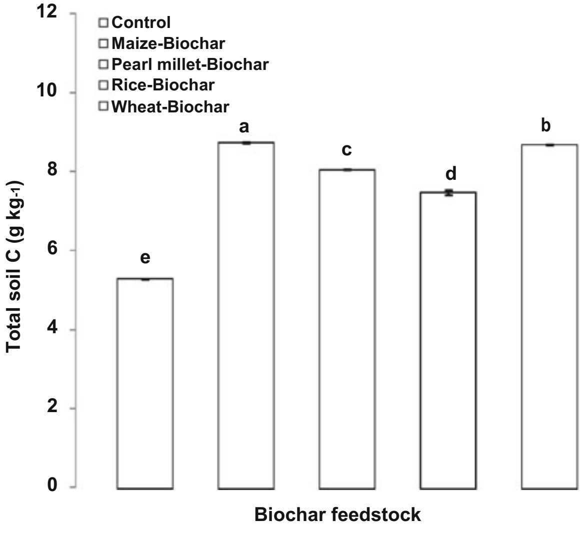


Fig. 11.7 Effect of different biochar on total soil carbon at the end of 1 year of carbon mineralization, the bars with different lowercase letters are significant according to Duncan's multiple range test at $P = 0.05$. *Source*: Purakayastha et al. (2015)

(pH = 8.1), addition of biochar increased C sequestration as native soil organic carbon (SOC) mineralization was minimal (Singh and Cowie 2014). The application of biochar in acidic soil emits more CO_2 in comparisons to alkaline soils. It was reported that addition of olive biochar in acidic soils increased two-fold CO_2 emissions and decreased N_2O emissions by 68% (Wu et al. 2018).

11.11.4 Soil Texture

The role of soil texture has its significance in achieving SOC stability through addition of biochar. The addition of biochar had a significant impact on the SOC stabilization in coarse-structured Al-rich Ultisol as compared to fine textured Mn-rich oxisols (Butnan et al. 2017). The higher clay content in soil reported to enhance SOC stabilization (Bationo et al. 2007). Gleysols had higher C sequestration potential than Nitosols and Acrisols (Haefele et al. 2011) on application of biochar at a fixed dose of 41 Mg ha^{-1}. Biochar-C stabilization was found to be more in oxisols than the soils dominated by permanent charged minerals (Vertisol and Entisol) or sand (Inceptisol) (Fang et al. 2014).

11.11.5 Interaction of Biochar with Native Soil Organic Matter

As biochar is porous in nature, it has higher affinity for natural organic matter (Kasozi et al. 2010). Alternatively, biochar containing labile-C may have a stimulatory effect on native soil C mineralization. The positive priming could occur if biochar acts as a metabolic C source, nitrogen, phosphorus and micronutrients (Chan and Xu 2009) or even a habitat favouring increased microbial heterotrophic activity (Thies and Rillig 2009). The presence of biochar in soils also enhanced the degradation of more labile-C sources such as ryegrass residue (Hilscher et al. 2009). Another study using 16 chars and two soil types, about a third decreased and a third had no effect on SOC respiration (Spokas and Reicosky 2009). Clearly, overall priming direction and magnitude varied greatly with soil and biochar type. One apparent trend, however, is that, for a given biochar biomass type, priming effect on total C oxidation generally decreased with increasing combustion temperature. For 250, 400, 525 and 650 °C biochar, the average priming effect over 1 year was 16, 9, 5 and 12, respectively (Zimmerman et al. 2011). In addition, negative priming was more prevalent in the two soils with the lowest SOC and least potentially mineralizable SOC. The native SOC is an important parameter that decides the C sequestration potential of soils. It was reported that soil with low SOC on application of biochar simulates mineralization of labile C (Singh and Cowie 2014). It was reported that Oxisols with higher native SOC (4.39%) mineralized less CO_2 than the Inceptisol with low SOC content (0.95%) (Fang et al. 2014). Purakayastha et al. (2015) studied stability (C efflux study) of rice, wheat, maize and pearl millet biochars at 400 °C and reported that maize biochar was found to be the most stable showing reduced C mineralization by protecting the native soil organic C (Fig. 11.8).

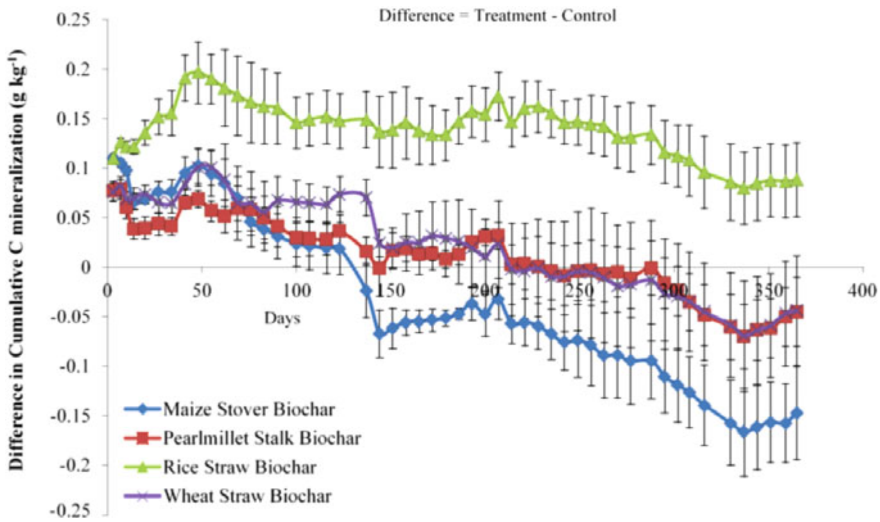


Fig. 11.8 Changes in carbon mineralization (CO_2 efflux) from soil with BC compared to the respective control treatments without BC addition. Error bars show standard errors ($n = 4$). *Source*: Purakayastha et al. (2016b)

Contrarily, rice biochar exhibited higher C mineralization. It is evident that the benefits of C sequestration through biochar are more visible in soils which are lower in C than soils relatively higher in C (Yadav et al. 2017). The interaction of soil and biochar showed that same biochar behaved differently when applied in soils with different organic matter content (Purakayastha et al. 2016b). It was reported that wheat straw biochar at 600 °C showed positive priming effect when applied in a soil (Ultisol) with lower organic matter but showed negative priming effect in a soil (Mollisol) with higher organic matter (Purakayastha et al. 2016b).

11.12 Effect of Biochar on Greenhouse Gas (GHG) Emissions

Many instances evidenced that biochar application to soil has a very good response over the transformation and retention of C and N in soil, which over the time regulates the mechanisms and finally improvise the sink capacity of GHG and reducing the emissions. The recalcitrance nature of stable aggregates can increase the shelf-life of biochar-amended soil C over time and reduce the emissions of GHGs (Spokas et al. 2009; Spokas and Reicosky 2009). Contrarily, there are also reports showing increased GHG emissions due to biochar applications in soil (Lin et al. 2017; Liu et al. 2014; Shen et al. 2014; Yanai et al. 2007). There is an obvious chance while multiple factors like feedstock type, pyrolysis temperature, nitrogen fertilizer rate and soil internal factors can significantly affect soil CO_2, CH_4 and N_2O fluxes after biochar amendment (He et al. 2017).

11.12.1 Biochar Feedstock on GHG Emissions

Quite a good number of researches undertaken in last two decades have given a clear-cut indication that the rate of GHG emissions from biochar-amended soil largely depends on two factors: feedstock of biochar and soil types. Over two cropping cycles in a paddy field, China, wheat straw biochar application significantly reduced N_2O emission but CO_2 emission remained unchanged throughout the two cycles; while biochar showed its positive effect in reduced CH_4 emission in the second crop cycle while simultaneous improvement in soil quality. In acidic soils contrasting effects of olive biochar and corn biochar were observed owing to biochar's liming effect and soil pH played a crucial role here, without any visible effect at alkaline clay soil. The corn biochar addition decreased CO_2 and N_2O emissions by 11.8% and 26.9% in the acidic sandy soil, respectively, whereas addition of olive biochar in the same soil triggered two-fold higher CO_2 emission rate and N_2O emission decreased by 68.4% (Wu et al. 2018). Rittle et al. (2018) reported that biochar produced from agricultural residues promotes GHG emissions from soil over a short-term period and that happened more in wet condition in Brazilian soil. Across the nine biochars studied, they reported that swine manure-origin biochar (of lowest C:N ratio) resulted in the highest GHG emissions, while eucalyptus origin biochar (of highest C:N ratio) had resulted in lowest GHG emissions. In another laboratory study, woodchip biochar could resulted in reduction of CO_2, N_2O and CH_4 emissions from the soil, while the significant suppression was obtained only at biochar amendment levels $>20\%$ w/w (Spokas et al. 2009).

Muñoz et al. (2019) reported that the cow manure biochar decreased CO_2 and CH_4 emissions across volcanic and non-volcanic soils. On the other hand, in boreal Scots pine forests soil, wood-derived biochar amendment (applied at a rate of 5–10 Mg ha^{-1}) did not show any pronounced effect on soil CO_2 effluxes (Palviainen et al. 2018).

Using biochar as a bulking agent for composting has been proposed as a novel approach to solve the environmental trade-offs of compost (Sancez-Garcia et al. 2015; Steiner et al. 2010). Biochar-chicken manure co-compost could substantially reduce soil N_2O emissions compared to chicken manure compost (Yuan et al. 2017).

Criscuoli et al. (2019) tested woodchip biochar in this regard and found that variation in temperature (ranging 10–30 °C) did not affect soil N_2O emission but marginally affected CO_2 emission whereas showed negative impact on soil CH_4 uptake in a wide range of soil temperatures conducted in a pot experiment at growth chamber. In terms of interactions with feedstock source, biochar produced from biosolids led to a statistically significant increase in sink strength/reduction in source strength. When produced from lignocellulosic waste, biochar significantly decreased the CH_4 sink strength/increased the source strength. No other feedstock showed statistically significant effects on CH_4 fluxes (Jeffery et al. 2016).

Contrarily, the high N_2O emissions from the low-temperature green-waste biochar treatment indicate that the decline in NO_3—N observed in this treatment was probably a result of enhanced activity of denitrifiers causing rapid conversion and loss of NO_3—N in soil through N_2O emissions rather than an inhibition of nitrification (Yanai et al. 2007). Biochar amendment of upland soil has been generally accepted to mitigate nitrous oxide (N_2O) emissions. However, this is not always the case in rice paddy soil. In this connection, Lin et al. (2017) reported that wheat straw-derived biochar amendment of paddy soils increased soil pH, which in turn increased the abundance and diversity of ammonia oxidizing bacteria and N_2O emissions. Previous study suggested that increased N_2O emission under biochar application was due to additional N input within the biochar (Shen et al. 2014) or increased denitrification resulting from biochar-derived labile organic C in paddy soils (Liu et al. 2014). However, biochar application has also been determined in increase of soil pH (Wang et al. 2012; Purakayastha et al. 2016b) and improved soil aeration (Zhang et al. 2010); such factors are associated with the abundance and community structure of ammonia oxidizing bacteria (AOB) and ammonia oxidizing archaea (AOA) (Chen et al. 2011; French et al. 2012; Li et al. 2018).

11.12.2 Pyrolysis Temperature on GHG Emission

Pyrolysis temperature of biochar preparation is crucial for GHG emissions from soil. High temperature biochar (willow, pine, maize, wood mixture) was reported to reduce N_2O emissions more than low-temperature biochar (Nelissen et al. 2014) and they reported that biochar application decreased both cumulative N_2O (52–84%) and NO (47–67%) emissions compared to a corresponding treatment without biochar. The application of municipal waste biochar, produced at 700 °C at the rate 10% (w/w) suppressed N_2O emission by 89% in a clay loam soil (Yanai et al. 2007). Soil amended with biochars produced from oak and hickory, pyrolyzed at 450–500 °C, showed a reduction of N_2O flux but increment in CO_2 flux in a long-term incubation experiment (Jones et al. 2011). Singh et al. (2010) demonstrated that after an initial spike of N_2O emission accounted, due to higher labile N content of biochar and microbial activity, the rate of emission decreased over time. Reduced H:C_{org} ratios in high temperature biochars indicate increased aromaticity, which is associated with the reducing effect of biochar on N_2O emissions (Cayuela et al. 2015). Stewart et al. (2013) reported that fast pyrolysis (with lower biochar yield) produced a highly recalcitrant biochar, derived from oak pellets (550 °C) that better sequestered C and reduced GHG emissions, where CO_2 was the primary GHG emitted, followed by N_2O.

Biochar has been shown to increase (Zhang et al. 2010; Spokas and Bogner 2011), decrease (Feng et al. 2012; Dong et al. 2013; Reddy et al. 2014), or have no significant effect (Kammann et al. 2012) on CH_4 emissions from soils. Some contrasting reports suggested that biochar-amended soils may enhance CO_2 and CH_4 emissions. Once a paddy soil was amended with biochar derived from bamboo and rice straw both pyrolyzed at 600 °C, the emissions of CH_4 and CO_2 were reduced by 51 and 91%, respectively (Liu et al. 2011). Another field study carried out in Australia applying cattle waste biochar produced at 550 °C indicated there was no significant difference in GHG fluxes (Scheer et al. 2011).

Rittle et al. (2018) showed that biochar production at higher pyrolysis temperature (600oC) with high C:N biochars (Eucalyptus origin) proved best to minimize GHG emissions. Biochars produced at high temperatures caused a statistically significant increase in CH_4 sink strength/reduction in source strength following application to soils. Mid-temperature biochars (450–600 °C) led to significant reductions in CH_4 sink strength/increased source strength when applied to soil.

11.12.3 Soil Type and Nitrogen Fertilizer Rate

Biochar application to acidic soils (i.e. with a pH <6) resulted in the strongest effect size, causing an increase in CH_4 sink strength/decrease in source strength following biochar application (Fig. 11.9) (Jeffery et al. 2016). Conversely, addition of biochar to soils within the neutral pH range (i.e. 6–8) showed a decrease in CH_4 sink strength/increase in source strength. Application of biochar to soils with a pH > 8.0 did not show any response to biochar application. Biochar effects on CH_4 flux interact with N fertilizer rate (Fig. 11.9). Application of N fertilizers caused a strong increase in CH_4 sink strength/decrease in source strength in the presence of biochar at rates <120 kg ha^{-1} but no response at higher rate. Biochar increased potential nitrification rates when soil ammonium concentrations were high following fertilizer application, thus enhancing N_2O emissions in the Biochar + Nitrogen treatment early in the season which were likely nitrification associated (Edwards et al. 2018). However, it was reported that over the full growing season, biochar application reduced cumulative N_2O emissions in Biochar + Nitrogen plots to levels similar to the unamended control (Fig. 11.10). The study demonstrates that biochar can have dynamic effects on soil N_2O emissions and the underlying microbial processes that depend on changing edaphic conditions, such as soil inorganic nitrogen availability and moisture, over the growing season.

11.13 Epilogue

Biochar being a highly carbonized product with higher stability in soil emerged as one of the residue management strategies for long-term C sequestration in soil for mitigating climate change. This approach is a win–win strategy while transforming huge amount of residues generated into useful products like bioenergy, bio-oil, syngas and biochar. Biochar prepared from feedstock having higher lignocellulosic material, e.g. wood biomass at higher pyrolysis temperature be having higher C sequestration potential than that prepared from low lignocellulosic material, e.g. straw biomass or manure. Biochar interacts with soil organic matter in a complex way to show either positive, negative or no priming effect, the magnitude varies with soil and biochar type.

Biochar when acts as a source of labile C and nutrients could cause positive priming effect on native soil organic matter, while biochar when adsorbs the refractory pools of soil organic matter in its porous structure might cause negative

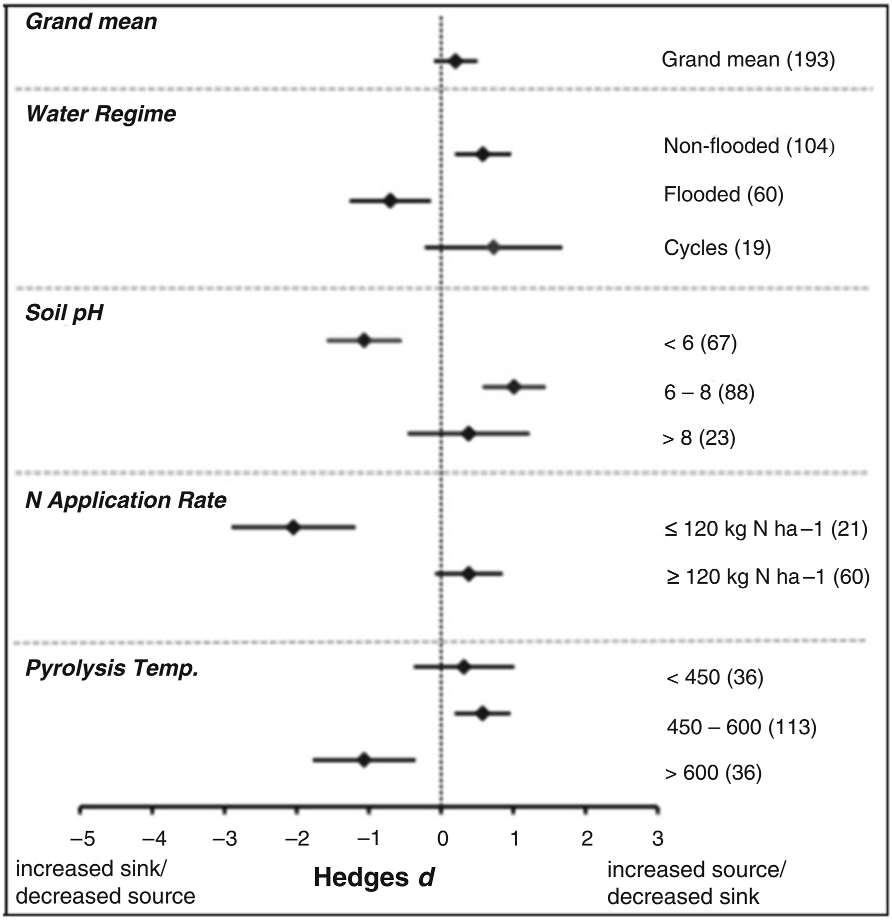
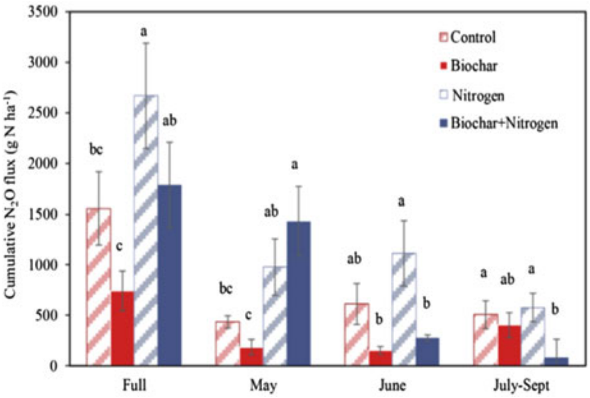


Fig. 11.9 A forest plot of Hedge's d calculated from published literature grouped by experimental water regime, soil pH pre-biochar amendment, N fertilizer application rate and biochar pyrolysis temperature. Points show means, bars show 95% confidence intervals. The numbers in parentheses indicate the number of pairwise comparisons on which the statistic is based. (For an explanation of the Hedge's d metric see text). *Source*: Jeffery et al. (2016)

priming. Carbon sequestration by biochar is likely to be less in soils relatively higher in native-C than in soils relatively lower in native-C due to stimulation of native C loss by biochar application. Besides C sequestration, biochar addition can be effective for reducing CH_4, N_2O and NO emissions from soils. However, the effect of biochar is highly dependent on its physical and chemical composition, feedstock from which it is prepared, pyrolysis temperature and soil type. The established literatures indicate that soil and biochar properties, as well as management conditions, must be considered to exploit biochar's full potential to mitigate GHGs emissions and minimize trade-offs. Low temperature, slow pyrolysis maximize

Fig. 11.10 Effects of biochar and N fertilizer addition on cumulative N_2O flux for the full growing season (Full), early season (May), mid-season (June) and late season (July–September). Error bars represent one standard error of the mean ($n = 4$) and letters indicate statistically significant differences among treatments for a given time period. *Source*: Edwards et al. (2018)



biochar production and thereby also C sequestration potential. However, research on biochar suggests that biochar prepared at higher pyrolysis temperature is more effective at mitigating CH_4 and N_2O emissions. Which one has the greatest potential to mitigate climate change thus remains to be established by employing life cycle assessment approaches. It is an established fact that the pH and ash contents of biochar increased with pyrolysis temperature while CEC of biochar decreased. Therefore high temperature biochar warrants its application to either neutral or alkaline pH soils but this biochar could be suitable for acid soils owning to derive extra benefits of biochar as a liming material. For making the biochar technology be more popular among the farmers, its production cost need to be lowered down and this is possible if the biochar originates from the bioenergy platform as an industrial by-products. Thus the biochar technology could be a win–win strategy which provided an opportunity to transform huge residues to transform into bio-oil, bioenergy, syngases and mitigating climate change by reducing GHGs emissions and enhancing C sequestration potential of soils.

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Biochar Role in Mitigation of Greenhouse Gas Emissions from Agricultural Soils

12

Waqar Ashiq and Asim Biswas

Abstract

Global warming is an important issue of the twenty-first century. Robust attention is needed to mitigate the negative impacts of global warming and climate change on environmental health which ultimately impact humans and other animals on planet earth. Different sectors release greenhouse gases (GHGs) into the atmosphere which contribute to global warming and climate change. Agriculture, forestry, and land-use change is one of the sectors releasing a significant amount of GHGs into the atmosphere. Major GHG emitted from agricultural soils is nitrous oxide (N_2O) which has 298 times more global warming potential than carbon dioxide (CO_2). Different strategies have been used in agriculture to reduce the GHG emissions from soil including fertilizer management, nitrification inhibitors, diversified crop rotation, biochar (BC) application, etc. Biochar is a black material produced by thermochemical conversion of organic waste in the absence of oxygen. The BC application received enormous attention after 1998 and became the focal point of multidisciplinary research. It also impacts GHG emissions from agricultural soils, however, different factors impact the BC performance to reduce GHG emissions from soils including BC application rate, feedstock, pyrolysis temperature, pH, C:N ratio, soil texture, pH and land use, etc. Studying all these factors in a single study is laborious and expensive. However, the results from different studies are combined in the form of meta-analysis to compare the impact of different factors on BC performance to mitigate GG emissions. Here we summarized the key findings from latest meta-analysis conducted on multiple published studies on BC's role to impact GHGs emissions.

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Possible mechanisms of how BC application impacts soil physicochemical properties and processes are also discussed.

Keywords

Global warming · Climate change · Pyrolysis · Carbon dioxide · Nitrous oxide · Methane

12.1 Introduction: Climate Change and Agriculture

Greenhouse gas (GHG) emissions are a source of global warming and climate change (FAO 2014; IPCC 2019). Three main GHGs (CO_2, CH_4, and N_2O) contribute more than 90% towards global warming (Hansen et al. 2000; IPCC 2013). Among other economic sectors (like transportation, energy production, and industry) agriculture and land-use change is also a significant source of GHG emissions to the atmosphere and contributes 24% of global anthropogenic GHG emissions (FAO 2014; IPCC 2019). These gases are released by different agricultural management practices including fertilizers application, livestock farming, dairy manure storage and application to soil, tillage, and organic amendments which impact soil respiration, methanogenesis, nitrification, denitrification processes (Ashiq et al. 2021; Baah-Acheamfour et al. 2016; Bavin et al. 2009; Chapuis-Lardy et al. 2007; Dziewit et al. 2015; Skiba et al. 1993). Biochar (BC) applications to soil modify soil biogeochemical properties and impact GHG emission (Castaldi et al. 2011; Laufer and Tomlinson 2012; Liu et al. 2012, 2018; Zhou et al. 2017). Biochar research started in 1998 and gained substantial attention over the years in the fields of environmental sciences and ecology, agriculture, chemistry, and engineering (Fig. 12.1). According to a scientometric analysis, the cumulative number of

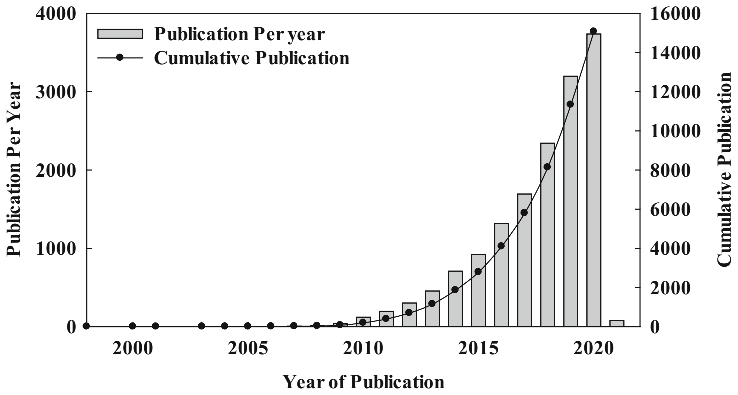

Fig. 12.1 Number of publications per year and the cumulative number of publications on biochar from 1998 to 2021. Data downloaded from Web of Science on 20th December 2020 using the word "biochar"

publications on BC reached over 15,000 in 2020. The purpose of this chapter is to summarize the key findings of this research from different meta-analyses, review articles, and research evaluating the impact of the application of different types of BC, application rates, aging, soil, climate, and land-use variations on GHG emissions at the global scale.

12.2 Biochar

Biochar is a porous, amorphous, stable, and low-density carbon material obtained by baking organic materials such as manure, forest leaves, organic waste, algae, sewage sludge, and wood (Atkinson et al. 2010; Laufer and Tomlinson 2012; McHenry 2009; Shackley et al. 2009). According to the international biochar initiative (IBI), BC is defined as "a solid material obtained by thermochemical conversion (pyrolysis) of biomass in an oxygen-limited environment" (IBI 2020) (Fig. 12.2). After pyrolysis, the less stable carbon (C) in feedstock biomass is converted to recalcitrant C that is resistant to decomposition (Baldock and Smernik 2002; Lehmann 2007). BC has multifaceted uses in various fields including an alternative strategy for utilization of agricultural waste into agricultural input, enhancement of soil health and quality (Nguyen et al. 2017), remediation of heavy metals and metalloids contamination, removal of organic contaminants, and reduction in their bioavailability, climate change mitigation, and soil C sequestration (Blanca Pascual et al. 2020; Cely et al. 2015; Hassan et al. 2020; Kołtowski et al. 2016; Lehmann et al. 2002). Besides being a rich source of C (Khare and Goyal 2013; Laird 2008; Matovic 2011), other properties like large surface area, porosity, high cation exchange capacity (CEC) (Randolph et al. 2017), and more adsorption sites (Mukherjee et al. 2014) improve soil physicochemical and biological properties. These include retention of soil nutrients (Uzoma et al. 2011), increased water holding capacity (Basso et al. 2013; Randolph et al. 2017; Ulyett et al. 2014), mitigation of greenhouse gas (GHG) emissions (Castaldi et al. 2011; Laufer and Tomlinson 2012; Liu et al. 2012, 2018; Zhou et al. 2017), and increased soil microbial communities and soil contaminants removal (Park et al. 2011; Wang and Liu 2017; Zhang et al. 2013).

Biochar properties such as pH, CEC, C content, C/N ratio, density, and pore size vary according to the type of feedstock, pyrolysis temperature, and residence time (Wang and Liu 2017). For example, by increasing pyrolysis temperature from 350 °C to 500 °C, hydrogen, oxygen, O/C, and H/C ratio were decreased while pH, ash, and C contents of BC increased at the same time (Wang and Liu 2017). According to a meta-analysis ($n = 533$), Hassan et al. (2020) reported that variations in pyrolysis temperature affected BC pH, surface area, pore size, ash content, hydrophobicity, O/C, and H/C ratios, and BC from hardwood and softwood had higher surface area and C content, whereas those derived from manure and grass had higher oxygen and mineral constituents. Also, manure and grass derived BCs were less stable and aromatic as compared to wood BCs. Therefore, both production technology and the composition of feedstock significantly influenced BC properties (Hassan et al. 2020). In addition to BC properties, soil (pH, texture, etc.) and climate

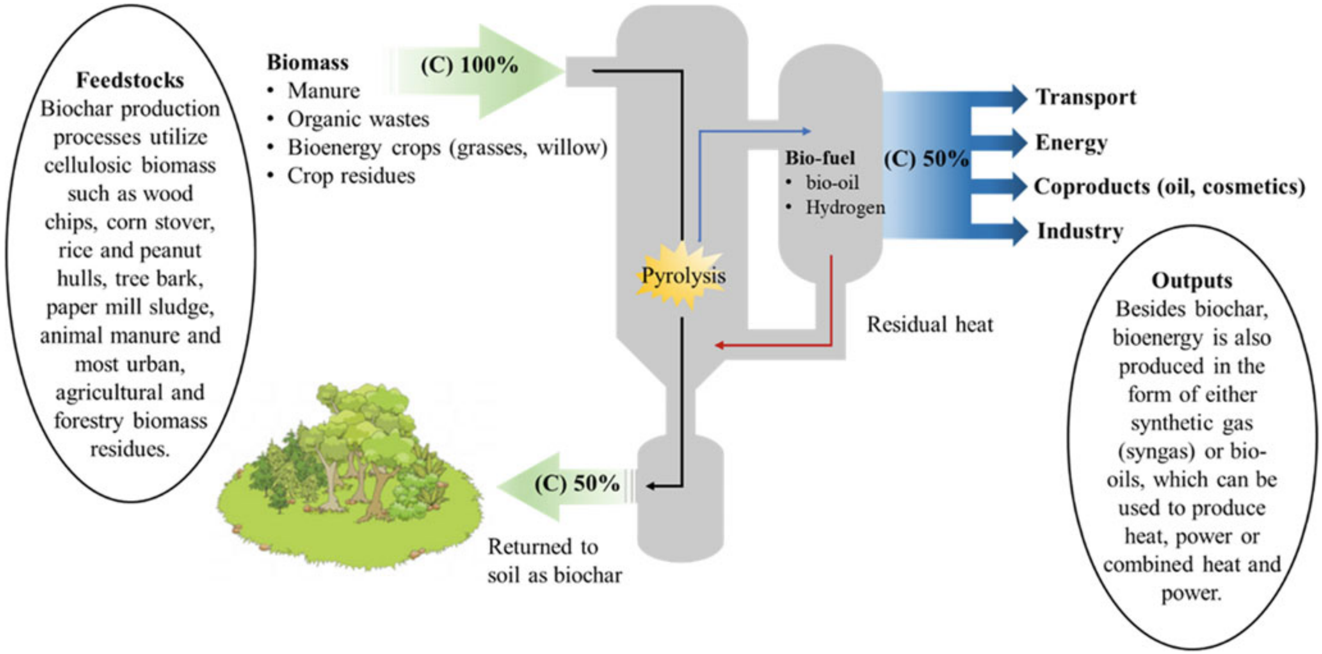

Fig. 12.2 BC production process. Adopted from (IBI 2020), courtesy of Johannes Lehmann

(tropical, subtropical, temperate, and polar) variations, BC application rate, BC aging in soil and land-use variations impact the effect of BC addition to soil properties and processes which influence GHG emission, C sequestration, and crop yield (Blanca Pascual et al. 2020; Cely et al. 2015; Hassan et al. 2020; Kołtowski et al. 2016; Lehmann et al. 2002; Prapagdee and Tawinteung 2017).

12.3 BC Role in GHG Emission Mitigation

In a global meta-analysis of 129 studies, Zhang et al. (2020) analyzed the impact of BC application rates, duration of the experiment, and soil and management conditions on CO_2, CH_4, and N_2O emissions and concluded that BC application increased average CO_2 emission by 78 kg C ha^{-1} d^{-1}, and CH_4 emission by 0.20 kg C ha^{-1} d^{-1}, whereas it decreased N_2O emission by 0.02 kg N ha^{-1} d^{-1}. In another meta-analysis (n = 96), He et al. (2017) reported an overall decrease in $CO_2$and N_2O emission from agricultural soils by 30.9% and 22.1%, respectively, whereas no impact was observed on soil CH_4 emissions. In contrast to Zhang et al. (2020) and He et al. (2017), who reported increased CH_4 emissions, Jeffery et al. (2016) reported in a quantitative meta-analysis (n = 42) that BC has the potential to reduce CH_4 from flooded rice fields which are a prominent source of global CH_4 emissions. These differences result from various BC and soil characteristics. In another meta-analysis (n = 61), Song et al. (2016) reported that BC application generally increased CO_2 emissions by 19% and decreased N_2O emission by 16% (−16%; sink), whereas no impact was observed on CH_4 emissions. However, when the separate analysis was carried out for paddy and upland soils, it was found that BC decreased CO_2 and N_2O emissions by 5% and 20%, respectively, and increased CH_4 emission by 19% from paddy fields. Whereas in upland soils, BC increased CO_2 emissions by 12%, decreased N_2O by 18% while it had an uncertain impact on CH4 emissions.

The above-mentioned meta-analyses reported the impact of all or some of the factors (e.g. BC application rate, duration of the experiment, feedstock, BC pH, soil pH, and soil texture) which control soil properties and GHG emissions. The key findings of these meta-analyses along with discussion are discussed below.

12.4 Biochar Application Rate

Biochar application rate is a major factor that controls soil biogeochemistry and GHG emissions (He et al. 2017; Song et al. 2016; Zhang et al. 2020). Low BC application rates of BC (10 t ha^{-1}) increased $CO_2$and CH_4 emission by 20% and 15%, respectively (Fig. 12.3). Increasing the rate of BC application to 40–80 t ha^{-1} leads to negativeCH_4 emissions (−30%) and BC > 80 t ha^{-1} resulted in negative CO_2 emissions (−36%) as compared to control (Zhang et al. 2020). The weighted response ratio of N_2O was negative at all BC application rates (<10, 10–40, 40–80, and > 80 t ha^{-1}), however, the soil became a stronger sink of N_2O at BC >80 t ha^{-1}(Zhang et al. 2020). A high rate of BC application was also reported to

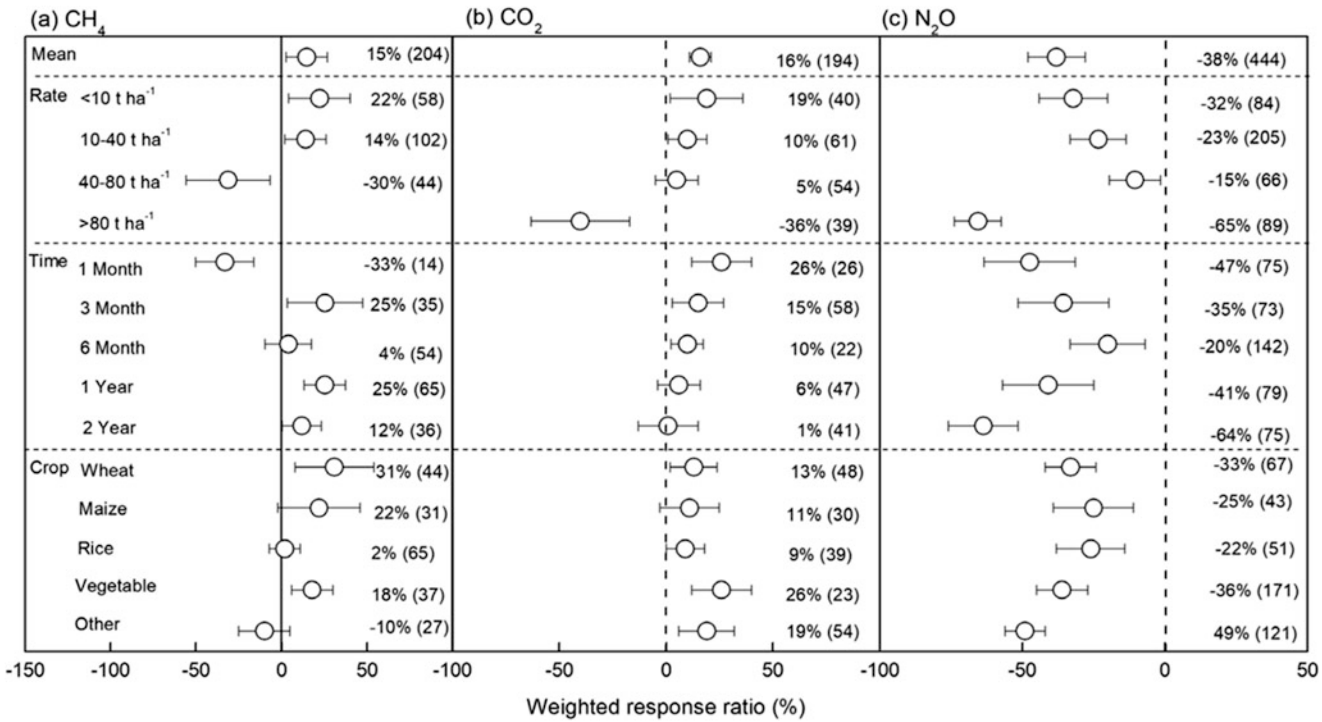

Fig. 12.3 The response of (**a**) methane (CH_4), (**b**) carbon dioxide (CO_2), and (**c**) nitrous oxide (N_2O) emissions (%) to the rate and time of biochar application. The numbers in parentheses represent the sample size. Source (Zhang et al. 2020)

decrease N_2O emissions by He et al. (2017). Contrarily, a low BC application rate (<10 t ha^{-1}) was observed to be more effective as compared to 20, 30 40, and > 40 t ha^{-1} in reducing CO_2 response ratio under field conditions by (Song et al. 2016). However, in laboratory experiments, BC at an application rate between 30 and 40 t ha^{-1}was more effective in reducing the CO_2 response ratio. These differences might be attributed to the duration of each laboratory (ranging from <30 days to >90 days) and field studies (ranging from 6 months to 3 years) (Song et al. 2016). High BC application rates increase available nutrients for microbes and might promote complete denitrification (N_2)(Lorenz and Lal 2014), and contribute to the suppression of soil N_2O fluxes (Cayuela et al. 2015). Due to the high cost of BC, it is not always possible to add high amounts of BC at a field scale unless its cost of production is reduced by local production. However, in some studies, BC had been used up to 80 t ha^{-1}. Nevertheless, this high rate of BC application might be cost-effective if used to grow crops with a high economic return.

12.5 Biochar Application Time/Experiment Duration

The experiment length also impacts the observation of different results of BC on GHG emissions (Song et al. 2016). However, the limited impact was observed by Zhang et al. (2020) and He et al. (2017) (Fig. 12.6). By increasing the experimental duration (1, 3, 6, 12, and 24 months), the weighted response ratio of $CO_2$was decreased as 26%, 15%, 10%, 6%, 1%, respectively, the CH_4 emissions as −33% (sink), 25%, 4%, 25%, 12%, respectively, and N_2O emissions as −47%, −35%, −20%, −41%, and − 64%, respectively. It shows that over time soil became a stronger sink of N_2O, whereas CO_2 emissions also dropped from 26% (increase) to 1%. Contradictory impacts of BC addition and experimental duration to soil had been reported on CO_2 and CH_4 emission depending on types of the experiment (i.e., filed, pot, or laboratory incubation). The response ratio of CO_2 varied from 1.29 to 1.05 and for CH_4 it varied from 0.8 to 1.2 for laboratory and field-based studies, respectively (Song et al. 2016). However, for accurate estimation and field-scale BC recommendation, long-term field-based studies should be evaluated for the actual impact of BC addition in GHG emissions under field conditions.

12.6 Land Use

Four land uses were compared to their response to BC application and GHG emissions by Zhang et al. (2020) including wheat, maize, rice, and vegetables. The weighed response ratio of CH_4 and CO_2 was more in wheat and vegetables, whereas N_2O had a higher (less negative) weighted response ratio in maize crop after BC application. Biochar increased soil CO_2 emissions by 13, 11, 9, and 26% in wheat, maize, rice, and vegetable production system, respectively. Similarly, CH_4 emissions were increased by 31, 22, 2, and 18% in wheat, maize, rice, and vegetable production system, respectively (Fig. 12.3). The soil was a strong sink of N_2O under vegetable production systems while a relatively weaker sink in maize production systems (Zhang et al. 2020).

12.7 Biochar Feedstock

Agricultural waste, residues, straw, poultry and manure, biosolids, and municipal waste are some of the feedstocks used for BC synthesis. Different types of feedstock have distinct physicochemical properties due to variations in elemental and structural composition (Hassan et al. 2020) and BC produced from these feedstocks responds heterogeneously to a different type of soil texture and pH conditions and has a profound impact on the soil ecosystem and GHG emissions. For example, wood-derived BC had higher lignocellulosic content as compared to grass-made BC (Enders et al. 2012). BC derived from willow (Salix viminalis L.) had higher pH, ash, and moisture content and lower CEC than pine (Pinus Sylvestris L.) derived BC (Nelissen et al. 2014). In a meta-analysis (n = 129), Zhang et al. (2020) compared the impact of BCs produced from shell residues, wood waste, straw waste, livestock manure, and municipal waste and reported that shell residues BC was most effective in reducing GHG (CH_4, CO_2, and N_2O), whereas wood waste was least effective in reducing CH_4 and CO_2 emissions and livestock manure BC was least effective in reducing N_2O emissions (though it was also a net sink). Conclusively, shell residue BC was most effective in reducing CO_2, CH_4, and N_2O emissions and reduced these emissions by 10, 17, and 58%, respectively. Whereas wood waste BC was least effective in reducing CO_2 and CH_4 and increased each of these emissions by 22% (Fig. 12.4). In another meta-analysis (n = 61), Song et al. (2016) compared the impact of BC derived from wood, straw, husk, and poultry manure and concluded that husk BC was most suitable for cropland in reducing GHG emissions when applied at an application rate of 20–30 tha^{-1}.

12.8 Pyrolysis Temperature

Pyrolysis temperature is the main factor controlling BC physicochemical properties and soil benefits (He et al. 2017). For example, increasing pyrolysis temperature from 350–450 °C increased pH and total C content of BC, 300–700 °C increased pH, electrical conductivity, particle density and porosity, and from 450–700 °C decreased BC particle size (Khanmohammadi et al. 2015; Mimmo et al. 2014). However, poultry litter lost almost 81% of its N when pyrolyzed at 500 °C though most of the OC was converted to recalcitrant C at 500 °C as compared to 300 °C (Guo et al. 2020). So, depending on the feedstock, pyrolysis temperature needs to be adjusted to get maximum soil and environmental benefits including soil health and GHG emissions. According to a meta-analysis (n = 129), BC pyrolysis temperature (<400 °C, 400–500 °C, 500–600 °C, >600 °C) did not affect CH_4 emissions, whereas CO_2 was only reduced (sink) by >600 °C and soil with BC produced at

500–600 °C became a stronger sink (−55%) of N_2O as compared to other temperature ranges (Zhang et al. 2020). Song et al. (2016) compared the impact of three pyrolysis temperature ranges on CO_2, CH_4, and N_2O emissions from 61 studies under field and four pyrolysis temperatures ranging under laboratory conditions separately. Under field conditions, BC produced at a temperature between 500 and 600 °C was most effective in reducing CO_2 emissions, and N_2O emissions were reduced by BCs produced at <500 °C, whereas 300–400 °C was most effective in reducing CH_4 emissions. In laboratory studies, CO_2 was effectively reduced by BC produced at 600–700 °C, and BCs produced at <500 °C were more efficient in N_2O reduction. He et al. (2017) reported (n = 91) a significant decreasing response of CO_2 ($P < 0.001$) and CH_4 ($P = 0.009$) emission with pyrolysis temperature indicating a reduction in these gases when BC pyrolysis temperature was increased from 200 to 800 °C, whereas no impact of pyrolysis temperature was observed on soil N_2O emission.

12.9 Biochar C:N Ratio

Different feedstock and pyrolysis temperatures result in variations in the C: N ratio of BC which impact the labile organic compounds in soil and regulate soil nutrient cycling and GHG emission processes (Clough et al. 2013; Zavalloni et al. 2011; Zimmerman et al. 2011). Khanmohammadi et al. (2015) reported that low pyrolysis temperature (300 °C) resulted in low C: N ratio BC as compared to 700 °C. Biochars produced at low temperature (<400 °C) had less recalcitrant C as compared to (>525 °C) and increase soil mineralization (Luo et al. 2011; Singh et al. 2012; Zimmerman et al. 2011). In a meta-analysis (n = 129), Zhang et al. (2020) reported the impact of a wide range of C/N ratios of BC (ranging from under 20 to more than 300) on GHG emissions. The C: N ratio was observed to be the most influential factor in controlling CO_2emissions. The BC with C: N > 300 decreased CO_2 emission, whereas CH_4 and N_2O were most effectively reduced by BC with C: N between 20 and 50. The BCs with C: N < 20 and > 300 increased N_2O weighted response ratio (Fig. 12.4). In another meta-analysis (n = 88), Borchard et al. (2019) reported the impact of 4 C: N ranges (<50, 50–100, 100–200, >200) on N_2O emission from soil. Significantly negative N_2O emissions were reported at all C: N ranges. However, BCs with C: N 100–200 were most effective in decreasing N_2O emissions and created a strong N_2O sink (52% N_2O emission reduction).

12.10 Soil and BC pH

Biochars having different pH ranges (<7, 7–8, 8–9, 9–10, >10) were studied by Zhang et al. (2020). Biochars which effectively reduced CO_2, CH_4, and N_2O emissions had pH between 9 and 10, 7 and 8, and 8 and 9, respectively (Fig. 12.4). Maximum CO_2, CH_4, and N_2O emissions were observed at pH range7–8, < 7, and 7–8, respectively (Zhang et al. 2020). In another meta-analysis,

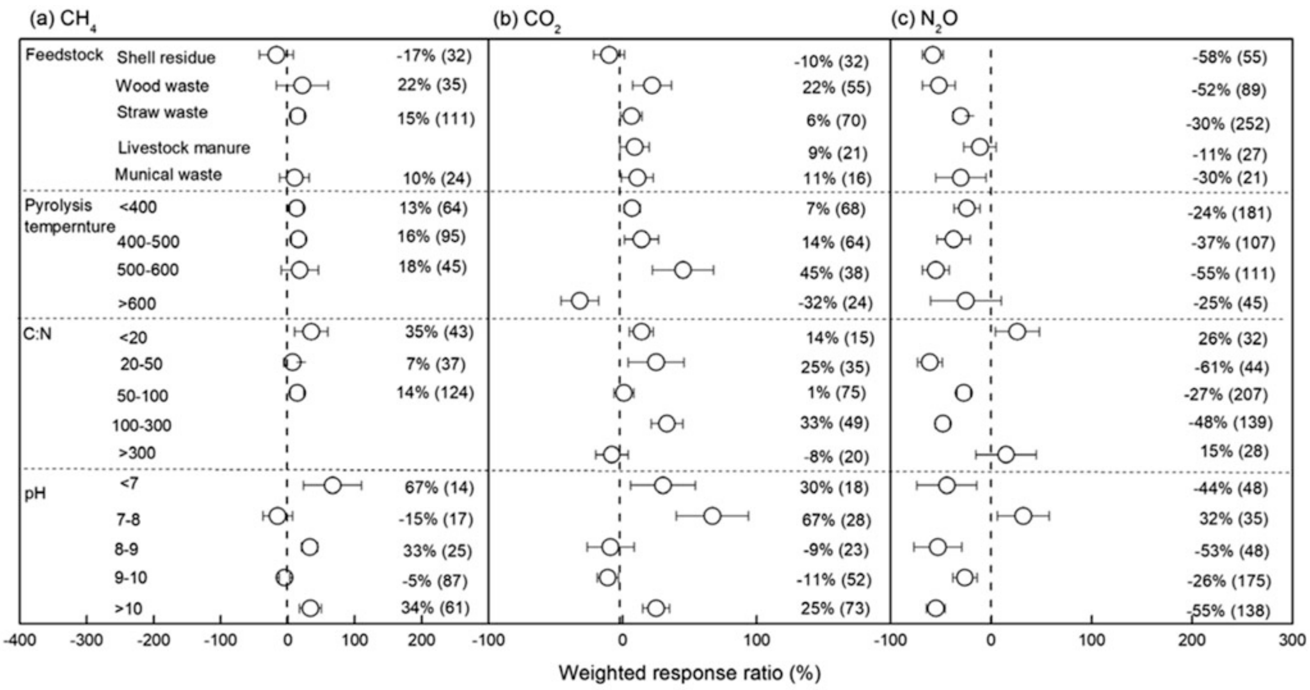

Fig. 12.4 Effect of biochar characteristics on (**a**) methane (CH_4), (**b**) carbon dioxide (CO_2), and (**c**) nitrous oxide (N_2O) emissions. The numbers in parentheses represent the sample size. Source, (Zhang et al. 2020)

He et al. (2017) observed that with an increase in BC pH, soil CH_4 and CO_2 emissions were significantly ($P < 0.001$) decreased, whereas there was no impact on N_2O emissions.

In addition to the pH of BC, soil pH is also a main controlling factor of soil processes. Both factors, soil and BC pH, affect the GHG emission processes including nitrification, denitrification, methanogenesis, and methanotrophy. Soil pH had a significant impact on GHG emissions after the BC application (Fig. 12.3). Soil with pH <5.5 resulted in relatively lowest CH_4 (as compared to 6.5, 7.5, and > 7.5) and higher N_2O emissions (less negative/weaker sink). Alkaline soil conditions (pH > 7.5) resulted in an exponential increase in soil N_2O absorption and soil sink capacity. Near-average CO_2 emissions were reported at a pH level between 5.5 and 6.5 (Zhang et al. 2020). In another meta-analysis, Jeffery et al. (2016) evaluated the impact of BC application on CH_4 emissions from flooded paddy fields and upland soils and concluded that BC application to acidic soils (pH < 6) significantly increased soil CH_4 sink (decreased CH_4 emissions). Significant reduction in CH_4 emission after BC application to acidic soils was observed by both (Jeffery et al. 2016) and (Zhang et al. 2020). The possible explanation for this reduction could be either the change in methanotrophic community structure by reducing aluminum toxicity in acidic soil after BC application (Dunfield et al. 2007; Xia et al. 2020).

12.11 Soil Texture

Soil texture impacts bulk density, aeration, air circulation, and air diffusion in the soil and affects GHG emission processes. Variations in soil texture also impact the role of BC on GHG emissions. Overall, less CH_4 and N_2O emissions were reported from sandy soil, while lower CO_2 emissions from loamy soil after BC application by Zhang et al. (2020). He et al. (2017) found that CH_4 emissions were decreased from coarse soils after BC application, whereas increased from fine soils. A possible reason for higher CH_4 emissions from fine soil might be the blockage of BC porous structure by clay particles which decreased aeration.

12.12 Discussion

Among all factors, the top three contributors affecting CH_4 emissions from soil were soil and BC pH, and BC application rate, and for CO_2 were BC C/N ratio, BC pH and application rate while N_2O was mainly affected by BC application rate, soil pH, and soil texture (Fig. 12.5). He et al. (2017) also reported that these three GHGs were mainly impacted by BC feedstock source, soil texture, and BC pyrolysis temperature. Individually, wood BC was more efficient in reducing soil CO_2, CH_4, and N_2O emissions as compared to herb and biowaste BC (He et al., 2017).

Biochar application reduced CO_2 emissions by 16–26% probably due to the sorption of CO_2 on its surface (Ashiq et al. 2020). Biochar had a higher surface

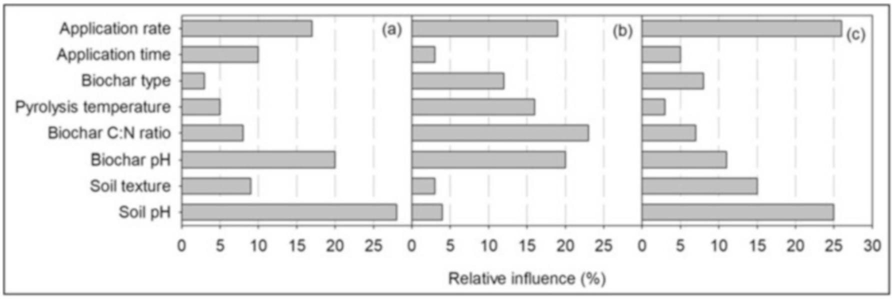

Fig. 12.5 The relative influence (%) of predictor variables for the boosted regression tree model of (**a**) methane (CH_4), (**b**) carbon dioxide (CO_2), and (**c**) nitrous oxide (N_2O) emissions. The variables are the rate and time of BC application, BC qualities (type, pyrolysis temperature, carbon-to-nitrogen (C:N) ratio, and pH), and soil properties (soil texture and soil pH). Source (Zhang et al. 2020)

area and reduces the availability of labile C to microorganisms (Brennan et al. 2015). Some studies also reported that BC induces a negative priming effect on soil organic matter and slows down its breakdown. There are different mechanisms proposed in literature which explain how BC reduces CO_2 emissions; (i) BC increases sorption of enzymes which breakdown soil organic matter, (ii) BC induces changes in microbial metabolism, (iii) BC enhance soil aggregate stability, and (iv) BC shifts microbial communities enhancing the bacterial taxa with low C turnover (Sheng and Zhu 2018; Spokas and Reicosky 2009; Zheng et al. 2018).

The increase in soil CH_4 emissions under some circumstances was observed which could be due to alleviation of C limitation for microbes after BC application increasing methanogenic archaea activities. BC also facilitates CH_4 oxidation and decreases CH_4 emission by suppressing methanogenesis by increasing oxygen supply in soil (Feng et al. 2012; Karhu et al. 2011; Kim et al. 2017; Yu et al. 2013). Ashiq et al. (2020) reported a reduction in CH_4 emission by 184–293% after BC application. BC application had been observed to increase the methanotrophic proteobacterial abundance which decreases CH_4 concentration (Feng et al. 2012; Liu et al. 2011). These variations in CH_4 emissions after BC application could be attributed to different soil textures as coarse soil had been reported to decrease and fine soil increases CH4 emissions after BC applications due to variations in soil aeration and blockage of BC pores due to clay particles.

Average N_2O reduction was 31% after BC application which was attributed to the changes in microbial communities involved in nitrification and denitrification (He et al. 2017). The BC increases soil aeration and ammonium and nitrate adsorption on its surface limiting substrate supply for nitrifiers and denitrifiers (Berglund et al. 2004; Laird et al. 2009; Lehmann et al. 2006; Yanai et al. 2007). The enhanced aeration and adsorption of inorganic nitrogen to BC surface decrease denitrification and N_2O emission (Fig. 12.6) (Ashiq et al. 2020; Bai et al. 2015; Laird and Rogovska 2014; Lan et al. 2017; Steiner et al. 2008; Yanai et al. 2007). BC enhances complete denitrification in the soil leading to reduction to N_2O to N_2 by stimulating

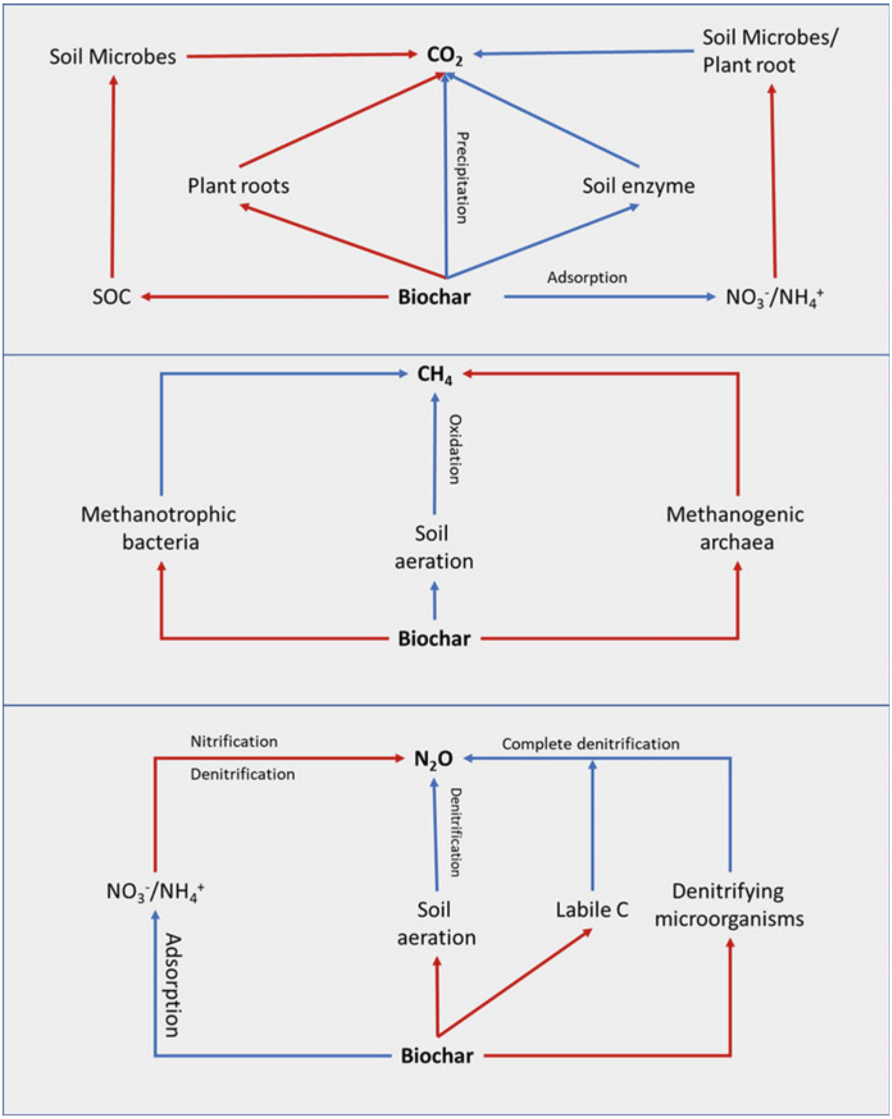

Fig. 12.6 Potential mechanisms of soil greenhouse gas (GHG) fluxes in response to biochar amendment. The red line and blue line represent the positive and negative regulations, respectively. Adopted from (He et al. 2017)

nosZ genes and facilitating electron transfer to denitrifying microorganisms in soil which converts N_2O to N_2 (Fig. 12.6) (Anderson et al. 2011; Cayuela et al. 2013).

Biochar is a useful tool to decrease GHG emissions from agricultural soils including flooded paddy fields. However, the selection of a specific type of BC is suitable for the soil type. For example, Song et al. (2016) concluded that husk BC was most suitable for cropland as compared to wood, straw, and poultry manure in reducing GHG emissions when applied at an application rate of 20–30 t ha^{-1}. Similarly, according to Zhang et al. (2020), shell residue BC was most effective in reducing GHG emissions from agricultural soils. Recently, there had been research on BC enrichment and designer BC (Aamer et al. 2020; Sigua et al. 2020). The purpose of BC enrichment is to allow for added nutrients to become available for plant growth so that the adsorption of nutrients does not restrain crop growth. However, the impact of BC enrichment needs to be further explored to evaluate its impact on GHG emissions. Designer BC is an interesting concept as BC with specific characteristics could be produced and used for different soil texture and pH conditions.

Biochar does not decrease all three GHGs (CO_2, CH_4, N_2O) in many cases. Therefore, there is always a trade-off between these GHG emissions in terms of total contribution (in terms of GWP in CO_2 equivalents). To further take BC research into agricultural fields and access its impacts on GWP and GHGs emission on a crop yield basis, we need to further explore and conduct a meta-analysis of only field-based studies which measured all three gases simultaneously to effectively compare the results on GWP and GHGs emissions per unit of crop yield (greenhouse gas intensity).

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Nanotechnology for Native Nutrient Mobilization and Enhanced Use Efficiency

13

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Abstract

Nanotechnology application in agriculture may serve to achieve sustainability towards global food production by enhancing more native nutrient mobilization, nutrient use efficiency, and maintaining soil health. Nanoparticle farming requires less nutrient, is less expensive, and produces more yield as compared to the conventional farming. It can regulate the nutrient delivery to the crops through the control release mechanisms. In general, 30% more nutrient mobilization in the rhizospheres and 2–20 times more efficiency of different nutrients were observed under nanoparticle farming. Plants that received nanoparticles are found to have overcome different abiotic stresses such as salinity, drought, cold, heavy metal, heat, flooding, etc. The miniature size, high specific surface area, and high reactivity of nanoparticles increase the bioavailability of nutrients. With the recommended doses of application they are found very safe and provide balance nutrition. They can also act as effective catalyst of plant and microbial metabolism.

Keywords

Nanosize nutrients · Nutrient use efficiency · Native nutrient mobilization · Soil enzymes · Crop yield · Soil health

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13.1 What Is Nanotechnology?

A technology under nanoscale, i.e. at least one dimension (length, breadth, height) of a particle should be within 1–100 nm. It is the study and application of extremely small particle/things across science fields such as chemistry, physics, biology, engineering, material science, and agriculture. It gives us complete control over the matter structure permitted by the laws of nature and allowing us to build any substances. Conversely, it is the technology of use of matter on an atomic, molecular, or super-molecular scale for industrial purpose. It has the potential to give a revolutionary impact on medicine, pharmaceutical, engineering, agriculture, diagnostics science, and purification process. It is one its way to make a big impact in our daily life. The modern nanotechnology actually started in 1981, when the scanning tunneling microscope allowed scientists and engineers to see and manipulate individual atoms. For inventing the scanning tunneling microscope IBM scientists Gerd Binning and Heinrich Rohrer won the Nobel Prize in physics in the year 1986.

13.2 Why Nanotechnology?

Because it can improve the existing industrial processes, materials, and applications by scaling them to the nanoscale in order to fully exploit the unique quantum and surface phenomena that matter exhibits at the nanoscale such as high surface area to volume ratio, high reactivity, effective catalyst, more penetration capacity, and triggering potential. Beside this, it has the potential to apply as carrier as well as controlled release ability. For example, nanotechnology has provided the feasibility of exploiting nanostructured materials as controlled release vectors for building of smart fertilizer to enhance nutrient use efficiency and reduce the cost of environmental protection; moreover, polymer-coated nanoparticles are used as agrochemical carrier due to its controlled release ability. It has huge potential to transform the people's life in the world better using cheap, light weight solar plastics that make solar energy widely available, reducing airborne pollutants, clean up toxic chemical spills, stimulation of crop growth, regulation of nutrient migration to environment, precision farming. Beside medical and engineering use nanotechnology it is helping every sphere of nutrition, protection and regulation in agriculture. Some of the major impacts of nanotechnology in our daily life are: (1) Powerful computer that are faster, smaller with long lasting batteries. The circuit made from carbon nanotubes could make it possible in maintaining the growth of computer power, allowing Moore's law to continue, (2) More accurate and faster medical diagnostic equipment which not only speeds up the delivery of medical care but also nanomaterial surfaces on implants improves wear and resist infection, (3) Nanoparticles improve their absorption within the body of pharmaceutical products that allow them to easier to deliver and can also be used as chemotherapy drugs to specific cancer cells, (4) Nanocomposite materials are lighter and stronger as well as more chemically resistant than metal that can very well be used as corrosion resistance by building vehicle parts which make vehicle more fuel efficient; moreover, nanofilters remove almost all airborne particles from the air before it reaches the combustion chamber which improves further gas mileage, (5) In fabrics nanoparticles/nanofibers can enhance stain resistance as well as flame resistance without increase in weight or thickness as well as stiffness of fabric, (6) Portable water treatment systems by nanosized particles of 15–20 nm wide can remove virtually all virus and bacteria and also very cost-efficient which improves the quality of drinking water, (7) Sports equipment can be made stronger and lighter by carbon nanotubes which bend less during impact as well as increase the force and accuracy, (8) Sunscreen made by nanoparticles effectively absorbs light and spreads more easily over the skin, (9) Nanoparticles use as fertilizer can mobilize more nutrient as well as enhanced nutrient use efficiency with control release and cost effective, (10) Nanoparticles used in food packaging have prolonged shelf life after reducing UV exposure, (11) Nanoclays used as drinking bottles are resistance to permeation of oxygen as well as carbon dioxide and moisture resulted increases shelf life by several months, (12) A large number of chemical sensors have been developed after using nanotechnology that detects the desirable chemicals at a very low level which is very important in surveillance and security systems in every places including laboratory to airport as well as can be used to accurately identify particular cells or substances in the body.

13.3 Nanoparticle Farming

Conventional farming does not satisfy the urgent requirement of rapidly growing global population due to crop damage by pest infestation, lesser nutrient availability, poor soil quality, natural disasters, and poor microbial buildup. Therefore, innovative technology is very essential to overcome this issue. Nanotechnology has shown the imminent potential to reform the present agricultural system by promising food security. Gradually nanoparticles are becoming most promising materials to transform modern agricultural practices. Nanoparticles may be classified based on size, morphology, physical, and substance properties. It may be carbon-based nanoparticles, ceramic nanoparticles, metal based nanoparticles, semi-conductor based nanoparticles, polymeric nanoparticles, and liquid based nanoparticles. As per shape, they can be classified as quantum dots, nanotubes, nanofibers, nanorods, nanosheets, aerogel, and nanoballs. It can also be classified as magnetic or non-magnetic nanoparticles. Presently there are varieties of nanoparticles based formulations such as nanosized fertilizers, pesticides, herbicides, fungicides, sensors are available for soil improvement, plant health management, and overall crop production. Nanoparticle farming opens a new avenue towards improving crop production. Due to small size and more surface area in comparison to volume it can intermixed well which leads to increased strength, heat resistance, and decreasing melting points. They have higher catalytic activity of plant and microbial metabolism and can better penetrate into the cell to trigger more enzyme release

Table 13.1 A comparison of conventional farming and nanoparticle farming

Character	Conventional farming	Nanoparticle farming
Fertilizer application rate	25–100 times more	25–100 times less
Nutrient use efficiency	2–20 times less	2–20 times more
Nutrient release	No match with the nutrient release with crop uptake	Controlled release of nutrients to match the uptake pattern of the crops
Solubility and dispersion	Less	More reduced soil absorption and fixation
Bioavailability	Less	Much more
Native nutrient mobilization	30% less than nanoparticle farming	Overall, 30% more than conventional farming
Loss rate	Loss is very high to the applied nutrient	Nutrient loss is minimum
Soil health	Deteriorating with time	Maintenance of soil health
Crop yield	Improvement between 12 and 18% of different crops	Improvement between 24 and 32% irrespective of crops

by plants and microorganisms. A difference between conventional farming and nanoparticle farming is shown in Table 13.1.

All the required plant nutrients such as N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, Mo, Zn, etc. can be prepared in nanoparticles form from the respective salts by the help of physical, chemical, aerosol, and biological technique. The most important physical methods are: grinding, thermolysis, sputtering, pulse laser deposition condensation, and microwave assisted synthesis. The important chemical methods are: sol-gel technique, poly-vinyl pyrrolidone method, co-precipitation technique, micro-encapsulation method, sonochemistry, colloidal method, hydrothermal synthesis, and micro-emulsions method. The important aerosol techniques used are: furnace method, flame method, electrospray technique, chemical vapor deposition, and physical vapor deposition method. Possible agencies for biosynthesis are: plant, algae, fungi, bacteria, actinomycetes, and yeast.

Modern nanoparticle farming based tools and techniques are found to have the potential to address many problems of conventional farming. It can maximize the output, i.e. crop yields, by applying minimum inputs, i.e. fertilizers, pesticides, herbicides, etc. Nanoparticle farming has the potential to increase plant photosynthesis rate, plant biomass and protein content, increase plant growth and extended harvest, reduce stress conditions, synthesize plant hormones and siderophore production as well as increase beneficial microbial activity in the rhizospheres beside more biological nitrogen fixation and phosphorus solubilization and mineralization.

13.3.1 Nanoparticle Application

Nanoparticles can be applied on plant leaves as foliage, soils as well as a seed treatment. It may also apply through drip, hydroponic, aqua and aeroponic. Foliar applied nanoparticles should be as smaller as possible because the pore size of the cell wall ranges between 5 and 20 nm; therefore, for easy entrance the diameter of the particle should be less than that. Nanoparticles after foliar application get transported from the site of application to the heterotrophic cells, which carried via the phloem vessels likely through the plasmodesmata. It can also be transported into the plants by forming complexes with membrane transporters and move through the vascular system. It is generally believed that nanoparticles with diameter less than 100 nm can easily penetrate through the stomata of leaves and were redistributed from leaves to stems through the phloem sieve elements. After entering into the plant system, it may transport from one cell to other cell through plasmodesmata and carried by aquaporins, ion channels, and endocytosis or by binding to organic chemicals.

13.3.2 Mode of Entry

Cell wall of plants acts as barrier for easy entry of nanoparticles into the plant cells. The important pathways of nanoparticles entry are: through shoots such as cuticle, epidermis, stomata, hydathodes, stigma, etc. and through roots such as root tips, rhizodermis, lateral root junctions, cortex, and any wounding. The uptake can use different path. Generally, uptake rate will depend on the size and the surface properties of the nanoparticles. For example, very small size nanoparticles can penetrate through cuticle, while larger particles can penetrate through cuticle free areas such as stomata, hydathodes, or the stigma of flowers. In general, smaller particles can move faster than larger particle sizes. The shape of the particle also plays a major role for movement. It was noted that the cube shaped particle moves faster than other shapes. After entering into plant cell, while moving, the particle may trigger different enzyme system to enable plants to release more enzymes for native nutrient mobilization. The nanoparticles also make plants more active and efficient while moving through the cell sap by triggering/hammering different enzyme co-factors. There are also enough possibilities of enlargement of pores or induction of new cell wall pores upon interaction with nanoparticles resulted enhanced nanoparticles uptake by plants. The mode of entry of nanoparticles as nanofertilizers is shown in Fig. 13.1. The nanoparticles when used as nanocapsules can enter the plant through the stomata orifices. During the process, the comical bond of the polymer wall of the nanocapsules can be broken or weakened by a critical amount of stress enzyme present. Plant cell stress enzymes are activated by mechanical, thermal, chemical, or biological stress. This stress sensitizes the plant during an attack and infection from fungi or bacteria. These polymer based nanocapsules are able to prevent this infection. In general, once close to the root, the chemical bond of the polymer wall is broken down by the organic acids or phenolic substances from the root exudates. These root exudates are typically

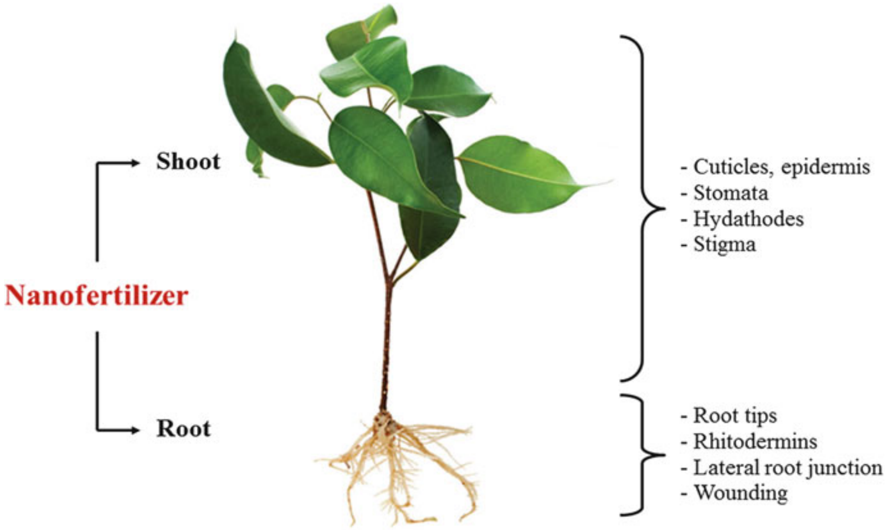

Fig. 13.1 Mode of entry of nanoparticles as nanofertilizer to plant body (modified after Tarafdar 2021)

released to enhance plant feeding during the plant growth process. Different procedures have made use of nanoparticles in plants, such as controlled release of bioactive substances as well as plant transformations.

13.3.3 Effect on Soil and Plants

Nanoparticles have important roles in physiological and biochemical processes of plants by increasing the availability of nutrients, which help in enhancing metabolic processes and promoting meristematic activities that result in higher apical growth and photosynthetic area. Many nanoparticles have an effect of synthesizing natural auxin and also can activate many enzymes involved in the biochemical pathways such as carbohydrate metabolism, protein metabolism, growth regulator metabolism, pollen formation, and maintaining the integrity of biological membranes. Nanoparticles also helping in increasing the plant growth promoting hormone content. Nanoparticles applied with irrigation water in drip are very helpful for plants when roots cannot provide necessary nutrients. It also reduces adverse environmental impact. On an average 30-50% increase in yield was recorded when nanoparticles as fertilizer applied through drip. Under sprinkler, the environmental losses are higher; therefore, doses should be minimized for nanoparticles application. It has been found that nanoparticles as sprinkler most suited for row, field and tree crops. The water can be applied over or under the canopy. Application of nanonutrients by hydroponics or aeroponic required volume control of the nanoparticles solution, as well as desired concentration for optimum effect. The maintenance of oxygen demand and pH are the important factors that need attention.

Soil application of nanoparticles is widely practiced but the availability of nutrients is much less as compared to the foliar application. Foliar feeding is the fastest way of correcting nutrient deficiencies and increasing the yield and quality of crop products with improved nutrient utilization and minimizes the environmental pollution. Nanocarrier in soil may help to deliver the nutrients in the right place and right times. Nanoparticles can be considered as smart delivery system due to its high surface area, sorption capacity, and controlled release efficiency. But in case of soil special attention should be taken on soil texture, salinity, plant sensitivity of salts and soil pH before choosing the particular nanoparticles. The nanoparticles may also be formed in soils as a result of biotic processes.

Nanoparticles application gave better quality of crop and horticultural products than conventional fertilizer application that was supported by many research studies. For example, fiber quality of cotton has tremendously improved by nanoparticles application in terms of strength and uniformity ratio; the application of nano-nutrient has led to increase in yield and protein content of peanut; nanoparticles of Zn have increased the oil content of sunflower, etc. Influential effect of nanoparticles on different crops may be due to increase in plant growth hormone and photosynthesis rate. The nanoparticles have greatly impacted the conventional delivery systems by eliminating the limitations such as leaching, degradation by photolysis, hydrolysis, and bio-instability in the atmosphere. Nano-encapsulated agrochemicals showed stability, solubility, time-controlled release, enhanced targeted activity, and less eco-toxicity with safe and easy mode of delivery, thus avoiding repeated application and safe for plants and environments but need safe limit of application.

13.4 Native Soil Microorganisms

Native soil microorganisms can influence the availability and movement of nutrient from soil to plants. The organisms generally present in soil may include bacteria, fungi, actinomycetes, algae, protozoa, archaea, and a variety of soil fauna including springtails, mites, earthworms, nematodes, ants, etc. Soil organisms play an important role in maintaining fertility, structure, drainage, and aeration of soil. They have enough potential to effect on physical properties and processes as well as biological contributions to carbon and energy fluxes and cycling of nutrients. They play an essential role in decomposing organic matter, cycling nutrients, and fertilizing the soils. They also play some of the vital roles in soil such as oxygen production, evolution, and symbiotic relationships. Rhizospheres (the region of soil in the vicinity of plant roots) are characterized by more microbiological activity than the soil away from plant roots. Bacteria are the most dominant group of microorganisms in soil and probably equal one half of the microbial biomass in the soil. The most common bacteria come under the genera *Pseudomonas, Arthrobacter, Clostridium, Bacillus, Achromobacter, Micrococcus*, *Flavobacterium, Chromobacterium*, etc. They mostly present in all types of soils. Fungi also dominate in all soils and next only to bacteria in abundance in soil. The fungi genera which are most commonly encountered in soil are: *Aspergillus, Penicillium, Cephalosporium, Gliocladium, Trichoderma, Alternaria, Verticillium, Rhizopus, Chaetomium, Rhizoctonia, Cladosporium*, etc. They are very efficient to degrade organic matters and help in soil aggregation beside producing substances similar to humic substances in soil. Actinomycetes are the other group of soil organisms, which have characteristics common to bacteria and fungi but possess sufficient distinctive features to designate them into distinct category. Unlike slimy distinct colonies of true bacteria which grow quickly, actinomycetes colony appear slowly, show powdery consistency, and stick firmly to agar surface. They differ from fungi in the composition of their cell wall. They do not have chitin and cellulose which is commonly found in the cell walls of fungi. The important actinomycetes genera are: *Streptomyces, Nocardia, Micromonospora, Actinomyces, Streptosporangium, Actinoplanes*, etc. The other important group of native soil microorganisms is algae. Numerically they are not as many as fungi, bacteria, and actinomycetes. By virtue of the presence of chlorophyll in their cells, algae are photoautotrophic and use carbon dioxide from the atmosphere and give out oxygen. Some of the common algae in agricultural soils belong to the genera *Chroococcus, Aphanocapsa, Lyngbya, Nostoc, Anabaena, Scytonema, Microcoleus*, etc. Some of the blue-green algae possess specialized cells known as heterocyst which are implicated in nitrogen fixation. In general native organisms are responsible for most of the nutrient release after decomposition of organic matter, they use the carbon and nutrients in the organic matter for their own growth and release excess nutrient into the soil which can be taken up by the growing plants. It has been noted that, in general, nanoparticles can influence the buildup of native soil microorganisms between 23% and 78% over original population under different cultivar, soil, and growing conditions.

13.5 Nutrient Mobilization

Nanoparticle regulates the delivery of nutrients in crops through controlled release mechanisms. Such a slow delivery of nutrients is associated with the covering or cementing of nutrients with nanomaterials. By taking advantage of this, growers can increase their crop growth because of consistently long term delivery of nutrients. For example, nutrients can be released over 40-50 days in a slow release fashion rather than the 4–10 days by the conventional fertilizers. Nanoparticle is providing balanced nutrition which facilitates the crop plants to fight against various biotic and abiotic stresses. Nutrient as nanoparticles found to help in mineralization, fewer fixations or immobilization, therefore increases the availability and mobility throughout the crop growing soils. Population of microbes which are mainly responsible for nutrient mobilization such as *Rhizobium, Azotobacter, Azospirillum*, Azolla, Mycorrhiza, P solubilizers, P mobilizers, Fe and Mn solubilizers, etc. has been enhanced due to different nanoparticle applications. The solubilization or mobilization of nutrient by microorganisms proves to be economic and beneficial as well as cost effective. It is a low cost technology and ecofriendly as well as

Table 13.2 Nutrient mobilization in the rhizospheres by nanoparticles application under different crops

Crops	Type of nanoparticles	Size of nanoparticles	% increase in microbial population	% increase in nutrient mobilization
Clusterbean	P and Zn	5–40 nm	56–87	26–32
Cauliflower	P and Zn	10–35 nm	75–128	30–36
Moth bean	Mg and Zn	8–32 nm	45–71	22–29
Mung bean	Mg and P	25–45 nm	50–91	28–33
Pearl millet	P and Zn	15–40 nm	62–95	29–34
Rice	N, P and Zn	22–42 nm	66–105	30–34
Wheat	Fe, P and Zn	12–51 nm	39–97	31–36

environmentally safe technology to enhance productivity and reduce environmental pollution. The improvement of rhizospheres population with the application of recommended doses of nanoparticles to some important crops is presented in Table 13.2.

The nanoparticles after applying in soil go to dissolve pools that either can be taken up by plants or migrated or bioaccumulated. It can also be sorbed or aggregated. The smaller particles are more mobile and are likely to be penetrating the ground water depth; however, the larger particles tend to retain in the upper layer of the soil that potentially causes soil clogging. The stability of nanoparticles in the soil is a function of their surface energy. In general, low surface energy particles are more stable. Soil is in general rich in natural nanoparticles. Artificial entry of nanoparticles in soil may have significant effect, as they may be the extremely resistant to degradation and have the potential to accumulate in the soil. Therefore, recommended doses of application of nanoparticles are very essential.

13.6 Nutrient Use Efficiency

Nutrient use efficiency is a fundamental challenge facing the present fertilizer industries. Use efficiency is the best defined as the increase in yield of the harvested fraction of the crop per unit of nutrient supply. Nanoparticle application as fertilizer has the potential to resolve the issues of low use efficiency. Nanostructure fertilizer exhibits novel physico-chemical properties, which determines their interaction with biological substances and process. Nanoparticle as fertilizer can increase the uptake efficiency in plants and developing DNA based nanosensor in a polymer-coated fertilizers would release only as much fertilizer as demanded by the crops/plant roots. Nanoparticle can delay the release of nutrients and extend the fertilizer and their effect period. It possesses unique physico-chemical properties that can fulfill plant root requirements more efficiently as compared to the conventional fertilizers. The fertilizer nutrient also can be encapsulated within a nanoparticle by coating with a thin polymer film or emulsion as nanoscale dimension or encapsulated inside the nanoporous material. The higher mobility of nanoparticles leads to transport of the

Table 13.3 A comparison of nutrient use efficiency of different size particles (modified after Tarafdar 2021)

Nutrient	Chemical fertilizer	Nanosize particles
N	30–35%	80–85%
P	15–20%	58–65%
K	35–40%	82–88%
S	17–22%	75–78%
Fe	4–5%	80–82%
Zn	3–4%	78–80%
Cu	2–5%	77–81%

nanoformulated nutrients to all parts of the plants. Due to high surface area to volume ratio the effectiveness of nanoparticles as fertilizer becomes superior to the most innovative modern conventional fertilizers. Nutrient for plants encapsulated in nanoparticles increases the availability of the nutrient elements and ultimately uptake of the crops. Though the consumption of chemical fertilizer in India increased steadily over the years, the use efficiency of nutrients applied as fertilizers continues to remain low which actually pushes the cost of cultivation and enhances the threat of environmental degradation. Therefore, it is absolutely needed to improve the use efficiency of applied nutrients. Nanosize particles can solve this problem due to their small size and more surface area as well as slow and controlled rate of release. It has been noted that when fertilizer is used as nanosize particles the use efficiency of applied nutrients is increased by 2–20 times of different crops. Higher efficiency of nutrients applied as nanoparticles may be due to higher surface area, more photosynthesis with less consumption of nutrient elements. Due to high solubility in water and smaller size facilitating more penetration of particles into the plant system, as the reduced particle size packing more number of particles per unit area that provide more opportunity for contact and leads to more penetration and uptake. Improvement of nutrient use efficiency is an essential requirements for crop production economically and environment friendly. The inefficient use of nutrient inputs raises both the cost of cultivation and threat for biosphere pollution. A comparison of nutrient use efficiency of chemical fertilizer (particle size between 5000 and 30,000 nm) and fertilizer as nanosize particles (particle size between 5 and 80 nm) is shown in Table 13.3.

Since fertilizer nutrients are expensive and are used in large quantities, there is a compulsive need for maximizing use efficiency. Any increase in the use efficiency of fertilizer nutrient will lead to a substantial cut in nutrient requirements by the crops resulted a huge benefit by the farmers as well as the nation. Nanosize nutrient particle provides more nutrients via nanoscale plant pores. So, the application of nanoparticles as fertilizers facilitates its efficient uptake without incurring wasteful losses. Nanoparticles as fertilizer generally delay the release of nutrients and prolong the period for which the applied nutrient particles remain in plant utilizable forms. The higher mobility of the nano-size nutrient particles in nano form provides the leads to the transport of nanoformulated nutrients to all the parts of the plants resulted overall growth and productivity. It is already mentioned that the nanoparticles used as fertilizers have potential contributions in slow release of plant nutrients. The higher surface tension provided by the surface coatings of nanoparticles helps to hold the material more strongly than the conventional material surfaces.

13.7 Ways to Enhance Efficiency

Nanoparticles as nanofertilizers show higher use efficiency due to their specific properties than mega particles as fertilizer. The important properties which influence the more use efficiency are:

1. The nanoparticles have more surface area, mainly due to their very smaller size, that provides more sites to facilitate the different metabolic process in the plant system. Moreover, the nano treated plants have more photosynthesis rate with less consumption of desirable nutrient elements.
2. Nanoparticles have high solubility with different solvents such as water.
3. The less particle size facilitates more penetration and triggering of nanonutrients into the plant systems.
4. Due to larger surface area and the particle size smaller than the pores of root and leaves of the plants, they can easily penetrate into the plant system from the applied surfaces and thus easily can improve the uptake and nutrient use efficiency.
5. The reduced particle size not only increases specific surface area but also increases number of particles per unit area, which provide more opportunity to contact that also leads to more penetration and uptake.
6. The fertilizer element encapsulated in nanoparticles increases the availability and ultimately uptake of the plant nutrients to the crops.
7. Particles applied as nanoform prevent loss of nutrients through denitrification, leaching, fixation, volatilization, etc. in the soil.

Nanoparticles when used as nanofertilizers are absorbed and entered through the different plant parts efficiently due to their smaller size. They are then transported through apoplastic and symplastic pathways to the xylem, cross the endodermis, and then they move through the vascular bundles to the different parts of the plants. It has been shown that different classes of nanoparticles are transported in the plants to the inside of the cells through endocytosis or through pores or channels. Nanoparticles as plant nutrient allow better dissolution, faster absorption, and assimilation by the plants as compared to the traditional fertilizers and this has been demonstrated for the plant nutrient elements such as N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, Mo, and Zn. One important point to remember is that the nanoparticles be used in a correct form and at a rate suitable for plants, which minimizes losses by leaching, gasification, or by competition with other organisms. One should remember that nutrient use efficiency not only depends on the plant's ability to take up nutrients efficiently from the soil, but also depends on the internal transport, storage, and remobilization of nutrients. Nanoparticles also influence the genetic variations within and among the crops, which may also affect the nutrient use efficiency. There may be scope of manipulating the expression of genes by nanoparticles, involved in the internal mobilization of nutrients within plants, thereby improving the utilization.

13.8 Nanoparticles on Plant Productivity

It depends on the combination of various vital factors such as soil fertility, good quality irrigation water, appropriate light intensity and temperature among other environmental factors, so that any deviation in one or more of these factors causes adverse effect on plant productivity. Drought, heat, salinity, water logging, and cold, among others, are major abiotic stress that cause huge losses to agriculture globally by reducing yield and product quality. These stresses either individually or in combination negatively affect the morphological, physiological, biochemical, and molecular changes in plant that ultimately decrease the productivity of plants. Different types of nanoparticles have been evaluated for their possible role in managing different abiotic stresses, for example, Zn as nanosize has been found to be defense responses and help plants to tress tolerance, nano-Fe has influenced antioxidant enzymes and chlorophyll content, Cu in nanoform improved fruit firmness and antioxidant content, etc. It was also reported that nanoparticles of Zn, Fe, Mg, and K may influence different plant growth hormones such as indole butyric acid, gibberellic acid, abscisic acid, salicylic acid, indole acetic acid, etc., which ultimately affect the plant growth and development. Damaging effect of UV-B radiation on photosynthesis can be alleviated by nanoparticles which improve the rate of photosynthesis by limiting oxidative stress, enhancing Chl biosynthesis, Rubisco activity, light absorbance, transport and transformation of light energy, absorbance of UV-radiation without scattering the useful visible one. Nanoparticles play important role in the protection of plants against various abiotic stresses by stimulating the activities of antioxidant enzymes, accumulation of osmolytes, free amino acids, and nutrients. It was found that application of nanoparticles at lower concentrations was effective in alleviating various abiotic stresses and enhanced plant growth and developments. Nanoparticles are being used as a vital tool for increasing the growth and productivity of crop plants under adverse environmental conditions including salt stress. For example, Si nanoparticles significantly alleviate salt stress and enhance seed germination and activities of antioxidative enzymes, photosynthetic rate, and leaf water content. Nanoparticles of Al_2O_3, TiO_2, ZnO, CeO_2, CuO, Fe_2O_3, $AgNO_3$, CeO_2, SiO_2, etc. are found to be generally effective against plant stress tolerance. Nanoparticles such as iron oxide and titanium dioxide changed the microbial community, influenced the colonies of nitrifying bacteria associated with roots. CuO nanoparticles influenced the composition and activity of bacterial community and decreased the oxidative potential of soil. ZnO nanoparticles enhance ammonification as well as increase dehydrogenase and hydrolase activities.

Nanoparticles can directly and indirectly influence physiology of the crop plants. They can alter in the formation of reactive oxygen species, catalase, peroxidase, superoxide dismutase activities beside chlorophyll, phenol, total lipids, and leaf

Table 13.4 Function of nanoparticles under different abiotic stresses

Abiotic stresses	Function of nanoparticles
Salinity	Keep plant leaves rigid and erect to improve light receiving, prevent chlorophyll degradation
Drought	Osmotic adjustment by regulating the synthesis of compatible solutes, helping regulation of gene expression, enhancing xylem humidity and water translocation
Cold	Reducing transpiration rate, stimulation of antioxidant system
Heavy metal	Helping in reduction of sodium uptake
Heat	Helping in co-precipitation
Flooding	Helping in complexation
Other environmental stress	Plays a considerable role in stomatal regulation, maintaining membrane integrity, retaining potassium content of the cells as well as plant water relations

protein contents. Nanoparticles also can influence the production of gum which help in soil aggregation, moisture retention, and carbon buildup. Nanoparticle induced polysaccharides enhances the water stress tolerance via enhancing more soil aggregation, root hydraulic conductance, and water uptake in plants and showing differential abundance of proteins involved in oxidation–reduction, ROS (reactive oxygen species) detoxification, stress signaling, and hormonal pathways. The overall role of nanoparticles under different abiotic stress is documented in Table 13.4.

13.9 Role of Nanotechnology on Soil Health and Crop Yield

Nutrient elements (N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, Mo, Zn, etc.) to plants can be delivered as nanosize with an accurate demand of the crop, which resulted more nutrient use efficieny as well as can avoid bulk requirements. The average expected yield was found to be much higher under nutrient as nanoparticles as compared to the chemical fertilizers, organic fertilizers, and different growth stimulators under different crops. The average crop yield increase due to application of different generations of fertilizers (Fig. 13.2) clearly depictted more average crop yield under the application of nanoparticles as fertilizer developed through nanotechnology.

Nanoparticles may act in a size and concentration dependent manner. Their effect is directly related to their particle size and concentration applied. Some of the nanoparticles showed adverse effect at higher concentrations; therefore, recommended doses and concentration should be applied for maximum benefit. Considerable increase in the root length, root area, dry biomass, and nodulation as well as overall crop yield was observed of different crops received nanonutrients. A significant improvement in beneficial enzymes (acid and alkaline phosphatase, esterase, dehydrogenase, cellulase, hemicellulase, lignase, nitrogenase) and microbial population (fungi, bacteria, actinomycetes, nitrosomonas, nitrobacter, *azotobacter*) was noticed under different crop rhizospheres with the application of

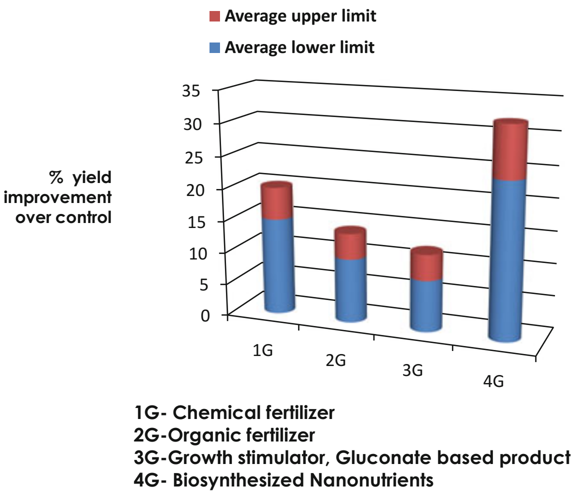

Fig. 13.2 Improvement of crop yield under different generations of fertilizer nutrients (modified after Tarafdar 2021)

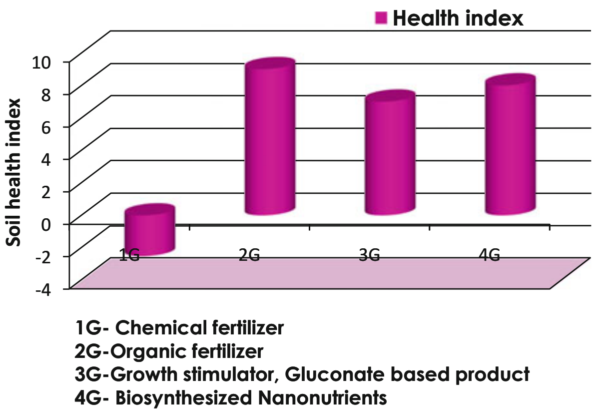

Fig. 13.3 The soil health level in continuous application of different types of plant nutrient as fertilizer (modified after Tarafdar 2021)

recommended doses of nanoparticles as nutrient. The nano-composites significantly affected and controlled the structure and permeability of the soil, increased the organic matter granule of the soil, increased nutrient storage and water holding capacity of the soil, promoted the action of microorganisms, regulated the soil C/N ratio and overall soil fertility. Nanocomposite has been developed in order to supply wide range of nutrients in desirable properties. These compounds are capable of regulating the inputs depending on the conditions of soil or crop requirements. Nanomaterials are porous and hydrated and as such they control moisture retention, permeability, solute transport, and availability of plant nutrients in soil. These nanomaterials also control the exchange reactions of dissolved inorganic and organic species between the soil solution and colloidal surfaces. It was reported that nano-composites can effectively be used to improve the yield and quality of the crops which are more prominent under cereals. The soil health level of recommended doses of application is shown in Fig. 13.3. Clay based nanofabricated material could be used in controlling release of nutrients and microflora control in the rhizospheres, ion-transport in soil–plant system as well as controlling emission of dust and aerosols from agricultural soil, zeoponics, and precision water farming. Nanoparticles as sensor also used for pathogen detection and detection of contaminated foods. Nanoparticles application opening a new avenues to improve not only nutrient use efficiency but also reduce nutrient builds up in soils and ultimately reducing its load in surface water bodies and checking contamination in drinking water. The fertility of soils can be enhanced by the application of nanoparticles. For example, nanozeolites can be used for soil conservations as slow release fertilizers. Magnetic nanoparticles can be efficient for removal of soil contaminants besides enzyme activation by nanoparticles in soil and plants. The major benefit of use of nanoparticles is ease of handling, enhanced stability, protection against oxidation, retention of volatile ingredients, etc. The metal nanoparticles present in soil may depend on the soil pH. The production of nanoparticles and its application in farming has expanded its chances in blending with the field soils. Nanomaterials can increase crop yield by increasing fertilizer nutrient availability in soil and nutrient uptake by plants. Nanoparticles can act in a concentration dependent manner and its effect on plant growth and seed germination is directly related to their concentrations. In some cases the higher concentration may be helpful to the plants but in majority of the cases higher concentrations have ill effect.

Application of nanoparticles influences the sustainable crop production by reducing nutrient losses, suppresses diseases and enhancing the crop yield with improvement of soil health. It can influence the key life of the plants that include seed germination, seedling vigor, root initiation, growth, and photosynthesis to flowering. Nanoparticles as fertilizer could successfully reduce the risks of pest and diseases, thereby minimizing the severity of yield losses and environmental hazards. The influential effects of nanomaterials on crop growth under unfavorable conditions can be explained by the increased activity of the enzyme system. For example, nanoparticles like nano ZnO or nano-SiO_2 application increase the accumulation of free proline and amino acids, nutrients and water uptake, and the activity of antioxidant enzymes including superoxide dismutase, catalase, peroxidase, nitrate reductase, and glutathione reductase, which ultimately improve plant tolerance to extreme climatic conditions. In addition, nanoparticles could also regulate stress gene expression. For example, a micro-array analysis showed a number of upregulated or downregulated genes by the application of Zn and P nanoparticles in pearl millet and clusterbean. The changes in uni-genes are found to be responsible for helping in carbohydrate metabolism, lipid metabolism, nucleotide metabolism, amino acid metabolism, and biosynthesis of secondary metabolism. However, the response of plants to nanoparticles varies within the plant species, their growth stages and nature of nanoparticles used. Nanoparticles also enhance the water stress tolerance via enhancing root hydraulic conductance and water uptake in plants and show differential abundance of proteins involved in oxidation–reduction, ROS detoxification, stress signaling, and hormonal pathways. Using of nanoparticles is found to be emerging solutions towards the abiotic stresses. It has been found that nanoparticles like Zn, Fe, Mg, K, etc. may influence different plant growth hormones

Table 13.5 Average yield increase (%) due to application of some of the nanoparticles as nanofertilizer (modified after Tarafdar 2021)

Crops	Nanoparticles applied	Average size	% yield increase
Rice	P	38 nm	27
Wheat	P K Zn	35 nm 22 nm 27 nm	31 28 27
Potato	P K Zn	33 nm 25 nm 19 nm	34 28 31
Tomato	P Zn	37 nm 21 nm	28 25
Moth bean	P Zn Fe	36 nm 22 nm 27 nm	30 22 21
Mung bean	P Zn Fe Mg	35 nm 24 nm 20 nm 16 nm	39 32 18 22
Pearl millet	P Zn Fe Mg	35 nm 22 nm 20 nm 15 nm	41 35 20 27

Doses applied: P – 40 mg/L, Fe – 30 mg/L, K – 40 mg/L, Mg – 20 mg/L, Zn – 10 mg/L

which also ultimately affect the plant growth and development. Nanoparticles such as iron oxide and titanium oxide changed the soil microbial community, influenced the colonies of nitrifying bacteria associated with roots. Copper oxide nanoparticles influenced the composition of bacterial community and decreased the oxidative potential of the soil. Zinc oxide nanoparticles enhance ammonification and increase the dehydrogenase and hydrolase activities. Nano-Zn particles as fertilizer are much more powerful to enhance total chlorophyll and leaf protein content of many plants even under adverse environmental and soil conditions, which ultimately enhances the extra yield and quality of the growing crops. The average yield increase by some of the crops due to nanoparticle application is documented in Table 13.5.

It has also been noted that nanoparticles as fertilizers on crops have absolutely no adverse effect on soil physico-chemical properties with the recommended doses of application.

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Nanotechnology in Environmental Soil Science

14

Tapan Adhikari

Abstract

Nano-materials play an important role regarding the fate, mobility, and toxicity of soil pollutants and are essential part of different biotic and abiotic remediation strategies. Efficiency and fate of nano-materials is strongly dictated by their properties and interactions with soil constituents. Investigations into the remediation applications and fate of nano-particles in soil remain scarce and are mostly limited to laboratory studies. Once entered in the soil system, nano-materials may affect the soil quality and plant growth. The fate of NMs is highlighted in soil-plant system with a critical evaluation of potential threats to the soil ecosystem. The environmental application and risk assessment of manufactured nano-particles (MNPs) in soil greatly depend on our understanding of the interactions between MNPs and soil components. Because of the complexity of the soil system and the very early stage of MNP research in soil, our understanding of MNP behavior in this system is very limited. Manufactured nano-particles are applied deliberately for soil remediation and are also released unintentionally through various other pathways to soil. Currently, the remediation of polluted soils using nanoscale zerovalent iron (nZVI), carbon nanotubes, and nano-fibers has become an emerging area with a huge potential to improve the performance of traditional remediation technologies. However, environmental concerns have also emerged regarding human and environmental health when nanotechnologies are released to ecosystems. The goal of this article is to highlight the environmental benefits and risks that arise when nanotechnologies are used to remediate polluted soils. Cutting-edge knowledge regarding the use of nano-particles to

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decontaminate soils has to move forward, but environmental quality, human health, and social welfare should also be ensured.

Keywords

Engineering nano-particles · Environmental concerns · Remediation · Soil pollution · Ecological risk

14.1 Introduction

Current promulgation of industrialization and urbanization activities entailing transportation, manufacturing, construction, petroleum refining, mining, etc., exhaust the natural resources and generate huge amounts of hazardous wastes which leads to soil, water, and air pollution. This masquerades several issues pertinent to soil-plant ecosystem and the environmental security that toughen the application challenges of conventional treatment technologies. Based on the current advancement in nanotechnology and its pivotal role to cover the vital requirement to examine and treat the rising hazardous wastes with lower cost, less energy, with higher efficiency, emphasis may be given for its wide spread application in our country. Fundamentally, the key points to briefly delineate the advantages of nanotechnology over conventional treatment technologies are (a) soil (application of nano-materials as amendment for phyto-remediation processes), (b) water (nano-composite treatment to decontaminate water), (c) air (treatment of greenhouse gases, volatile organic compounds, and bioaerosols via adsorption, photocatalytic degradation with nano-materials). Moreover, possibility of accumulation of some pollutants in food chains, like bioaccumulation of heavy metals and persistent organic pollutants (POPs) in biota and fishes, which causes major risks to human and wildlife.

Hence, an urgent requirement demands for the development of sustainable, efficient, and low-cost technologies to examine and properly treat toxic environmental contaminants. One of the most promising routes to revolutionize the environmental remediation techniques is “nanotechnology” which can be defined as a group of emerging technologies that work on nanometer scale (i.e., between 1 and 100 nm range) to produce materials, devices, and systems with fundamentally new properties and functions by controlling the size and the shape of matters (Ramsden 2009). The global momentum of nanotechnology has been well recognized due to its potential applications in many fields of pollution treatment (Brame et al. 2011) is offering leapfrogging prospects in the improvement and transformation of conventional remediation technologies. The noble properties such as thermal, optical, mechanical, electromagnetic, structural, and morphological properties provide the nano-materials with advantageous features for many applications where they can be explored as nano-adsorbents, nano-sensors, nano-membrane, and disinfectants. Considering the remarkable advances in nanotechnology, necessary steps may be taken urgently in our country to develop green, robust, and economic approaches for environmental remediation with the applications of nano-materials in, soil, water, and air and provides an expansive view on favorability of nanotechnology over the conventional technologies.

14.2 Soil Pollution and Nano-Remediation

The presence of hazardous compounds in the natural soil environment is the main source of soil pollution. Anthropogenic activities like mining, manufacturing, landfill sites, particularly those that are accepting industrial wastes (e.g., paint residues, batteries, electrical wastes, etc.) and application of municipal or industrial sludge to agricultural fields direct to heavy metal pollution in soils. Heavy metals can be considered one of the challenging soil pollutants because they are non-degradable substances and they will stay in the contaminated environment once they are introduced to it, the only exceptions are mercury and selenium, since they can be transformed and volatilized by microorganisms. When large areas of soil are polluted, treatments can be done in situ (on-site) or ex situ (removed and treated off-site), however, the traditional treatment methods for contaminated soil are cost-prohibitive and extremely difficult (Natural Resources Conservation Service 2000). As a result, the best way to protect the environment is by preventing the contamination of heavy metals or by hindering the spreading of heavy metals in soil by immobilization technique (Ma et al. 1993). Due to the fact that activity of heavy metals in soil is governed by sorption–desorption reactions with other constituents of soil, a wide range of amendment agents have been used to manipulate the bioavailability of heavy metals and to impede their diffusion in soil by inducing various sorption processes: adsorption to mineral surfaces, formation of stable complexes with organic ligands, surface precipitation and ion exchange. There are two types of amendment agents (Robinson et al. 2009): (1) Mobilizing agents, which increase the bioavailability and mobility of heavy metals and enhance their removal through plant intake and soil washing (i.e., phytoextraction process) and (2) immobilizing amendment agents that decrease the bioavailability and mobility of heavy metals and reduce their transfer to food chain by preventing their leaching to the groundwater (i.e., phytostabilization).

In recent years, nanoscale particles have gained a great interest for heavy metal immobilization in soil and groundwater. Two essential requirements should be met when using nano-particles as amendment agents including the following (An and Zhao 2012): (1) they must be deliverable to the contaminated zones and, (2) when removing the external injection pressure, the delivered nano-particles should remain within the confined domain (i.e., under natural groundwater conditions), where the delivered nano-particles will work as an immobile sink for capturing soluble metals. However, the rapid tendency of nano-particles to aggregate into micro- to millimeter scale aggregates results in losing their distinctive characteristics such as high specific surface area and soil deliverability. For the purpose of overcoming these problems, organic polymers such as starch and carboxymethyl cellulose (CMC) (He and Zhao 2007) are often attached on the nano-particles as stabilizers in order to prevent nanoparticle agglomeration through steric and/or electrostatic stabilization mechanisms and to improve the physical stability and mobility in soil and greater specific surface area.

Liang and Zhao (2014) investigated the effectiveness of starch-stabilized magnetite nano-particles for in situ enhanced sorption and immobilization of arsenate As

(V), the results indicated that water-leachable As(V) was greatly reduced as well as the toxicity characteristic leaching procedure (TCLP) leachability of As(V) was decreased. Phosphate compounds can be used as effective agents for in situ immobilization of heavy metals in contaminated soils, as demonstrated by immobilization of lead (Pb) where phosphate was commonly applied to soil either in its soluble forms such as phosphoric acid or solid forms such as synthetic apatite, natural phosphate rocks and even fishbone (with apatite being the effective composition). Therefore, a new type of apatite nano-particles was synthesized using CMC as a stabilizer in order to increase the dispersion rate of phosphate and immobilize lead in soil. It was suggested that the carboxyl and hydroxyl groups in cellulose molecules played an important role in inhibiting further agglomeration of nano-particles; moreover, in producing a stable lead phosphate compound, that is widely recognized as pyromorphite (Liu and Zhao 2013).

Zerovalent iron (ZVI) nano-particles are also used widely for in situ reductive immobilization of heavy metals in soil. The main drawback of ZVI nano-particles that are prepared using traditional methods is their ability to agglomerate rapidly or react quickly with the surrounding media (e.g., dissolved oxygen or water), resulting in losing in their reactivity and mobility in soil. The agglomerated ZVI particles are often in the range of micron scale; therefore, they are not transportable or deliverable in soils and thus, they are not applicable for in situ treatments. Accordingly, various ZVI particle-stabilizing strategies have been reported including modification of nZVI with several types of organic coatings, such as starch, polyvinylpyrrolidone (PVP), and sodium CMC. Cetylpyridinium chloride has also been used to control ZVI nano-particle agglomeration (Chen et al. 2004). Another problem that is limiting the engineering applications of iron-based materials is the cost factor due to the large amount of chemical reagents such as ferrous sulfate and ferrous chloride that are consumed during the material conventional preparation technologies. With intention to reduce the cost, Wang et al. (2014) successfully prepared CMC-stabilized nanoscale zerovalent iron from steel pickling waste liquor to remove Cr(VI) from contaminated soil and the results revealed that TCLP leachability of Cr(VI) reduced by 100%. However, the immobilization technique to remediate the contaminated soil imposes many problems. Firstly, despite both soluble and solid phosphates being reported as highly effective for heavy metal in situ stabilization on the laboratory scale, adding large amounts (e.g., 3% PO_4–3 dosage) of very soluble phosphoric acid or phosphate salts into the subsurface is limited not only by the cost of materials but also by the secondary contamination problems that arise due to the high solubility of phosphate which may lead to the contamination of groundwater and surface waters in the affected area by excessive nutrient input (eutrophication) (Park et al. 2011).

Secondly, Xu and Zhao (2007) stated that the CMC stabilizer is vulnerable to hydrolysis and, once it decomposes, its particle-stabilizing ability ceases and the fine residual precipitates end up in the soil phase. Finally the ecotoxicity of the immobilized chromium by CMC-stabilized ZVI nano-particles prepared from steel pickling waste. The results suggested that such remediation exerted an inhibitory effect on plant growth, which might be related to specific physicochemical properties of nZVI. There are several possible mechanisms by which fresh nZVI could enhance Fe uptake into plants; one possibility is that they penetrate the seed coat and are assimilated by the seed embryo. Another expected way for nZVI to enter the plant is via root epidermal cells by endocytosis (Slomberg and Schoenfisch 2012). Moreover, it was confirmed that carbon nanotubes are also able to penetrate the seed coat while supporting and allowing water uptake inside the seeds (Khodakovskaya et al. 2009).

14.3 Water Pollution and Nano-Remediation

Globally convenient access to clean and affordable water is one of the major challenges that needs immediate solution. Population growth, global climate change, and water pollution are the highest challenges that increase the struggles faced by water supply systems. In both developing and industrialized countries, water scarcity is exacerbated by human activities that play the greatest role in contaminating the natural water resources by releasing energy, chemicals, and other pollutants that deteriorate the water quality for other users. In addition, nature itself can be one of the contamination sources such as water storm runoff, animal wastes, etc. The United States Environmental Protection Agency (EPA) classifies water pollution into the following six categories: (1) plant nutrients, (2) biodegradable waste, (3) heat, (4) sediment, (5) hazardous and toxic chemicals, and (6) radioactive pollutants. Thus, water pollutants include organic pollutants, pathogens, industrial discharge containing heavy metals and different anions, etc. that are added to the water and cannot be naturally broken down and they tend to change the properties of the water body. Essentially, the wastewater treatment involves physical, chemical, and biological technologies and it usually occurs in four stages: (1) preliminary, (2) primary, (3) secondary, and (4) tertiary advanced treatment. The technologies that are generally used for water purification are coagulation and flocculation, sedimentation, dissolved air flotation, filtration, steam distillation, ion exchange, deionization, reverse osmosis, and disinfection. Materials usually used in these technologies are sediment filters, activated carbon, coagulants, ion exchangers, ceramics, activated alumina, organic polymers, and many hybrid materials (Hotze and Lowry 2011).

However, the conventional water treatment procedures might be costly and could release secondary toxic contaminants into the environment (Gaya and Abdullah 2008). Nanotechnology enables extremely efficient, flexible, and multifunctional processes that can provide a promising route, in order to retrofit aging infrastructure and to develop high performance, inexpensive treatment solutions which depend less on large infrastructures. The current advancements in nanotechnology spot the light on great opportunities to develop the next generation of water supply systems and expose the possibilities to expand the water supplies by affording new and cost-effective treatment capabilities that can overcome the major challenges faced by the current treatment technologies.

14.4 Sensing and Monitoring Systems

A major challenge for environmental remediation management is monitoring the emission of toxic substance like organic and inorganic pollutants, pathogens, and hazardous atmospheric pollutants, coupled with accurately assessing the extent and composition of these contaminants. Therefore, various analytical techniques have been employed in environmental pollution detection and monitoring, for instance, surface plasmon resonance (SPR) (Salah et al. 2012), high-performance liquid chromatography (HPLC) (Shintani 2014), gas chromatography–mass spectrometry (GC-MS) (Tranchida et al. 2015), supercritical fluid chromatography (SFC) (Ishibashi et al. 2015), capillary electrophoresis (CE) (Sánchez-Hernández et al. 2014), flow injection analysis (FIA) (Gerez et al. 2014), etc. Nevertheless, these techniques are inappropriate for routine environmental detection because of their high cost and time consumption in addition to their complicated requirements. The growing advances in nano-science and nanotechnology are having a remarkable influence on the field of environmental monitoring and sensing, where a large number of nano-particles have been introduced for detection and remediation of a wide range of contaminants in both gaseous and aqueous mediums. Many investigations have been carried out to develop high selectivity and sensitivity nano-sensors for monitoring different types of gases in the ambient air (Zhou et al. 2015) in order to prevent potential explosion or poisoning, particularly for odorless, colorless, and tasteless hazardous gases such as hydrogen and for poisonous and irritant gases such as nitrogen dioxide (NO_2) (Beheshtian et al. 2012).

Similarly, the application of nano-material-based sensors is widely studied for water quality monitoring by the detection of organism fecal pollution (Savichtcheva and Okabe 2006) such as fecal coliforms, total coliforms, *E. coli,* enterococci bacteriophages, and disease causing viruses and parasites (Theron et al. 2010) and detection of different types of trace contaminants (such as pesticides, phenolic compounds, inorganic anions, heavy metals). As any other chemical sensors, nano-particle-based sensors usually consist of two components: the receptor, which enhances the detection sensitivity and the transducer, a chemical or physical sense component (nano-material), that works with electrochemical, thermal, optical, and other detection principles (Su et al. 2012). The operating mechanism involves a charge transfer that occurs between pollutant molecules and the receptors, resulting in an electrical and/or optical signal that is related to the molecule type and number. Not to mention that in the case of bionanosensors, recognitions agents (e.g., antibodies (Volkert and Haes 2014), carbohydrates (Chen et al. 2011), aptamers (Li et al. 2009), and antimicrobial peptides (AMPs) (Cui et al. 2012) are presented as a third components and specifically provide the selectivity by interacting with antigens or other epitopes on the pathogens surface.

Moreover, to obtain nano-sensors with high sensitivity and fast response time, nanostructures such as nanorods, nanobelts, and nanowires were functionalized. For instance, tungsten oxide nanowires (WO_3-NWs) were functionalized with palladium for hydrogen gas detection and with copper oxide for high-performance hydrogen sulfide sensor (Park et al. 2014). As a matter of fact, nano-material-based sensors have shown great potential in the chemical and biological detection researches due to their physical, chemical, optical, catalytic, magnetic, and electronic properties as well as their high selectivity and sensitivity. Some examples of widely used nanomaterials in sensors technology include quantum dots (QDs) which can be benefited from their fluorescence properties to detect heavy metals, toxic gases, cyanotoxins, and pathogens (Feng et al. 2014). Metal nano-particles such as silver and gold nanoparticles rely on the changes in their color for pollutant detection (Salah et al. 2012). Furthermore, CNMs are facilitating the electron transfer between electrodes and electro-active species (Su et al. 2012) and they have been employed for monitoring of different pollutants and toxins. For instance, SWCNT and MWCNT were effectively used to develop electrochemical systems for monitoring of MC-LR in water below its WHO provisional concentration limit (Han et al. 2013). The specificity of MWCNT biosensor was improved by adding monoclonal antibodies specific to MC-LR in the incubation solutions and the performance of MWCNT array biosensor was enhanced by electrochemical functionalization of MWCNT in alkaline solution to enrich its surface with oxygen containing functional groups that permit the immobilization of MC-LR onto MWCNT array electrodes.

14.5 Environmental Risk From Nanotechnology

Among the applications of NMs, the use of nZVI is becoming one of the most prominent examples of a rapidly emerging technology with considerable potential benefits, many uncertainties and misconceptions regarding the fundamental features of this technology have made it difficult to engineer applications for optimal performance. For example, currently there are three basic fundamental uncertainties associated with the application of nZVI, such as (1) high concentrations of nZVI aggregate to produce micron size clusters which does not exhibit "true" nano-size effects; (2) the mobility of bare or uncoated nZVI will be less than the few meters under almost all relevant conditions; and (3) the potential risk to human or ecological health remains largely unknown (Tratnyek and Johnson 2006). These uncertainties highlight that our understanding of the basic processes involved in this technology is still evolving and incomplete. The major environmental concern is that the tiny nano-particles could end up in environmental bodies infesting drinking water sources harming the health of humans and animals (Oberdörster et al. 2006). Nano-particles present potential risks in terms of (1) dispersal—ability to disperse in the environment including potential long range transport; (2) ecotoxicity—ability to cause adverse effects to organisms in the environment; (3) persistency—ability to remain in the environment; (4) bioaccumulation—ability to bioaccumulate or bioconcentrate in higher order organisms; and (5) reversibility—ability for the removal or to reverse their original introduction from environment. Although nanotechnology is likely to represent a beneficial replacement of current practices for site remediation, research into health and environmental effects of nano-particles is urgently required.

Currently, standard methods to readily detect and monitor NMs in the environment are not up-to-date. For example, Kuhlbusch et al. (2011) stated that, a major drawback to the current state-of-the-art measurement devices is their lack of differentiation of background particles from NMs. Additionally, the majority of the devices available today are able to discriminate particles according to size, but not according to density. Little is known about the rates of aggregation and deposition of specific engineered NMs, due largely to complex nature of the system and the lack of instrumentation for measuring NMs at such small sizes and concentrations. As current research does not provide strong data to evaluate the fate and transport of NMs once incorporated in water, air, or soil it hinders the process of NMs risk assessment in the environment, further indicating the need for additional research in this field. In order to understand the risk of NMs in the environment both the dose–response effect of NMs and the exposure pathways determining how NMs enter an organism must be considered. Toxicity studies should not only focus on human and wildlife but also lower organisms as they make up the basis of food chains. Earlier research has shown that nano-particles can have adverse effects on pure cultures of bacteria like *Escherichia coli*, *Pseudomonas fluorescens,* and *Bacillus subtilis* var. niger where oxidation of the nZVI led to the production of reactive oxygen species in living cells (Diao and Yao 2009).

In addition, Fe2+ can enter cells creating oxidative stress which can damage their membranes leading to the leakage of intracellular materials and eventually cell death. Adverse nZVI effects were also observed in plant species. For example, Ma et al. (Ma et al. 2013) evaluated the phytotoxicity and accumulation of bare nZVI by two commonly encountered plant species, cattail (*Typha latifolia* L.), and hybrid poplars (Populous deltoids $\times$ Populous nigra) where nZVI exhibited a strong toxic effect on Typha at higher concentrations ($>$200 mg L^{-1}). nZVI also significantly reduced the transpiration and growth of hybrid poplars at higher concentrations with the upward transport to shoots minimal for both plant species. A lower population growth of earthworms, phyto-, and zooplanktons was also observed in the presence of NMs like nZVI (Keller et al. 2012). A number of studies have indicated toxicity of NMs to soil microorganisms such as CuO and Fe_3O_4 were found to cause changes in soil microbial communities caused by toxicity at 1% and 5% w/w dry soil (Ben-Moshe et al. 2013). In contrast, Fajardo et al. (Fajardo et al. 2012) reported that exposure of nZVI (34 micro g g^{-1}) and C60 (100 micro g g^{-1}) had little impact on microbial cellular viability and biological activity within the indigenous microbial population in the soils even at high concentrations.

This suggests that the toxicity may be strongly related with the bioavailability and solubility. Even if current production and subsequent release of NMs were estimated to increase to 100-fold, only three NMs are considered a major concern: Ag, nZVI, and ZnO. Of these, ZnO is the greatest concern since it exhibits toxic effects to all species tested. Hence, NMs release and its effects on the environment should be monitored closely, with special care given to the use of nZVI in soil and groundwater remediation as toxicity is observed at $>$0.5–1 mg L^{-1} (El-Temash and Joner 2012) and typical remediation concentration can range as high as 1–10 g L^{-1} (Grieger et al.

2010). Unlike larger particles, NMs can be taken up by cell mitochondria and the cell nucleus (Porter et al. 2007).

DNA mutations and major structural damage to mitochondria resulting in a cell death, has been demonstrated (Nel et al. 2006). These concerns over safety may limit the widespread applications of NMs for environmental remediation. Hence, to make this technology more beneficial than harmful, monitoring and intervention measures need to be implemented sooner than later. It is simple, environmentally friendly, and inexpensive thereby representing a technology which degrades contaminants sustainably which reduces the risk of the release of further toxic products and by-products into the environment mitigating the risk to aquatic and human health.

14.6 Strategies and Regulatory Measures

Strategies like green and microbial synthesis of nano-particles, or with the help of advanced engineering, viz. development of biomarkers to monitor nano-particles, combined the use of permeable iron barriers and nano-particles, etc. may be followed to improve the situation. Moreover, legal or regulatory measures require to formulating to examine stringently and control the utilization of nano-particles in the soil ecosystem. A pivotal issue crop ups from the widespread use of nanotechnology is how to control the development and deployment of nano-remediation technologies to exploit enviable outcomes and keep adverse outcomes at bay. United Kingdom made most important progress to identify nano-particles as new chemicals, which are controlled under existing chemical regulatory statutes (Bowman and Hodge 2007). However, developing nations should try to firmly follow nanotechnology regulations. For example, it is very difficult for the countries like India to cope up nanotechnology risks that may influence its huge population due to constraint of the resources, expertise, and political mandate (Barpujari 2011). Due to the lack of current legislations on nano-particles, a serious risk may pose for raw-material production, distribution, use and disposal processes. A comprehensive approach including advanced research, public education, media coverage, and integrated legislation will be vital to supervise the complexity of nanotechnology to thwart any detrimental effect due to nano-particles exposure. Update of current OECD test guidelines will lead to the development of new regulations along with guidance for appropriate and valid testing of the environmental fate and ecotoxicity endpoints for nano-particles. These assessments require to be amended in a timely manner with the progression of nanotechnology and must be tracked firmly to give meaningful, reproducible, and precise ecotoxicological information to prevent detrimental effect of nano-particles.

14.7 Recommendations

In India research work on nanotechnology particularly in the field of natural resource management still is in infancy. Endeavors to support research in nanotechnology in India started early in the millennium. But still there is a lot of scope for its expansion. The amount India invests on nanotechnology research is still very meager in comparison to other countries like Japan, USA, France, and China. The investment also from the private sector to nanotechnology research has been nominal. Research from academic institutions has pointed out that nanotechnology recorded a great impact on Indian market, like arsenic decontamination of water, water based self-cleaning technology for use in textile industry, etc. Indeed, it is really a worry, despite such mammoth potential the private sector is not endowing enough in nano-science research. Funding should be raised for long-term research programs with high-impact outcome. All over India, different research centers/institutes must work jointly so that the united efforts can direct to better results. A well-equipped central facility should plan and instigate the research activities. The administrative matters should be streamlined for new initiatives. Moreover, incentives for people skilled in the field should enhance, to magnetize highly talented personnel to join these research services.

14.8 Future Studies and Thrust

There are some future prospects and researchable issue in soil pertinent to nanotechnology are (1) development of Nano-sensor to monitor soil quality, (2) development of Nano-magnets for soil contaminant retrieval, (3) development of Nano-membrane for water treatment and purification, (4) establishment of baseline information on safety, toxicity, and adaption of NPs in soil and adequate life. Research needs to be undertaken for the assessment of the human and environmental risks associated with the application of this technology. Hence, there is a huge potential to dedicate systematic research knowledge on to developing large scale greener processes, which can further boost the application of nano-remediation at a commercial scale.

14.9 Epilogue

Nanotechnologies and nano-sciences have been very useful for delivering some materials, products, or services with better characteristics compared to their respective bulk material. Also, these areas have also provided some nano-sized materials to the environment. However, nanotechnologies have also been used to dissipate soil pollution. It is well known that some strategies to remediate polluted soils through nanotechnology might be accomplished, but some questions have to be answered prior the spread of nano-remediation, i.e., nano-particle toxicity has to be assessed while the standardization of techniques should be set by scientists and decision-makers worldwide. The cutting-edge knowledge regarding the use of nano-particles to decontaminate soils has to move forward, but environmental quality, soil, and animal health should also be ensured. Otherwise, these patents regarding modern nano-materials might jeopardize sustainability. Environmental damage due to increasing population and industrialization is a serious cause for concern. The advent of nano-remediation, using smarter engineered NMs can deliver cost effective and time saving in situ clean up procedures for large scale contaminated sites. Moreover, it can eliminate the need for treatment of the contaminated material by reducing the contaminant concentration to zero. With a rapid advancement of this technique, proper evaluation needs to be done to prevent any potential environmental or ecological hazards. The promising and innovative technology, together with the proposed improved understanding of nano-particles in both basic and field demonstrations in well characterized environments provides the prospect for exploiting nanoscale technology for environmental applications. The exacerbated human activities are convulsing the ecosystem balance by feeding the environment with large amounts of anthropogenic hazardous toxicants that pollute soil, water, and atmosphere and consequently threaten human public health. An attempt to adopt a compatible treatment technology for cleaning up all the wastes that are left behind the industrial revolution, this account simply compared with the application of propitious nanotechnology to conventional technologies in environmental remediation. It has been shown that nanotechnology exhibits remarkable features for advanced, robust, and multifunctional treatment processes that can enhance pollution monitoring, treatment performance, as well as overcome all the aforementioned barriers. In brief, nanotechnology has the potential to improve the environmental remediation system by preventing the formation of secondary by-products, decomposing some of toxic pollutants by zero waste operations, and prohibiting further soil contamination by converting the pollutants from labile to non-labile phases. Finally, nanotechnology will pave the way for versatile and vibrant systems which involve the cutting-edge techniques in sensing and monitoring of varieties of harmful chemicals and toxins in different environmental media.

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Importance of Soil Heterogeneity Study in Variety Testing Programs

15

Rahul Raman

Abstract

The exponentially growing population has triggered the need for more food. Lot of work is being done in the field of crop improvement and variety testing to develop high yielding varieties. But the question is whether modifying crops at molecular or gene level is the only thing required to improve yield? Is there any factor that may affect the yield of these elite varieties? Should we consider that factor in crop improvement and variety testing programs? The answer is yes. Soil heterogeneity is an important factor that may affect the yield of these elite varieties. Unfortunately, it is the least explored area in any crop improvement or variety testing program. Soil heterogeneity results in over- or under-application of inputs such as fertilizers or irrigation that affects crop growth and development. Same genotypes planted at different sites on a field varying in amount of nutrients or organic matter tend to perform differently. All these increases the complexity of agricultural research and slow down the process of varietal selection by breeders. Soil heterogeneity may occur at site, space, or time level. In the field condition, soil is rarely homogeneous. Variability exists and hence, should be explored in crop improvement and variety testing programs. There are several ways to do soil sampling—random sampling, grid sampling, or sensor-based to study soil variability but they are either not accurate, time-consuming, require resources, or complex to work with. UAV has emerged as a low-cost tool that provides near real-time data and is capable of mapping soil heterogeneity for moisture, nutrients, etc. It can be a great tool to consider in exploring the effect of soil heterogeneity on crop varietal growth and development and making decisions accordingly.

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Keywords

Soil heterogeneity · Soil variability · Crop improvement · Variety testing · Plant breeding · Genotypes · Variety · Soil moisture · Soil nutrients

15.1 Introduction

Since decades, impressive work is being done in the field of crop improvement and variety testing to feed the exponentially growing population. From plant phenotype to gene, a lot is being studied to improve the crops for better yield. In agriculture, yield is the 'king'. In field condition this yield is affected by several factors, one being soil heterogeneity. Soil variability or heterogeneity has been a least studied and explored area in any crop improvement and variety testing programs. While modifying crops at molecular level we often forget that soil is a factor that may affect the performance of these modified crops. Soil heterogeneity is a state where soil varies in the amount of element, nutrient, moisture, etc., at site, space, or time level. Soil heterogeneity can be spatial or temporal depending on the factors such as parent material, climate, vegetation cover, and disturbance caused by humans. Due to uneven distribution of clay contents, organic matter, nutrients, organic carbon, etc., in the soil at site, space, or time, any uniform application of fertilizers, irrigation, etc., may result in under- or over-treatment (Viscarra Rossel and McBratney 1998; Patzold et al. 2008). This under- or over-treatment of inputs may influence the morphology and physiology of crops, thus affecting their growth and development. Soil spatial or temporal variability not only affects crops development but increases the complexity of decision-making process.

15.2 Influence of Soil Heterogeneity on Crops Growth and Development

Spatial or temporal soil heterogeneity contributes to the variation in agricultural crops performance at site, space, or time level. Variability in soil texture, composition, or characteristics may affect physiology, morphology, and/or grain yield of crops (Adamchuk et al. 2010; García-Palacios et al. 2012; Kupisch et al. 2015; Kutuzova et al. 2015; Boenecke et al. 2018). Soil organic carbon (SOC) is one of the factors responsible for soil heterogeneity at spatial scale. Compared to the hot and dry region, SOC is higher in cool and wet areas and/or with higher forest cover in the topsoil (Adamchuk et al. 2010). Management practices such as tillage results in loss of soil organic matter (SOM). Land prepared with conservation tillage, no tillage, or reduced/shallow tillage tends to have a higher SOM and SOC compared to conventional tillage (Chen et al. 2009; Blanco-Moure et al. 2012). Microbes decompose this SOM and enrich the soil with nutrients. Long-term stabilization of SOM also serves as the storage for atmospheric Carbon. This SOC enhances soil water holding capacity and nutrient retention, thus increasing the crop grain yield (Wood et al.

2016; Poffenbarger et al. 2017). The enhanced water holding capacity and nutrients in the soil also support photosynthesis and crop biomass accumulation.

Soil type and texture are other factors that influence soil water holding capacity, and hence crop production. Fine soil (clay and silt) has higher water holding capacity than coarse soil (sand). Low cation exchange capacity (CEC), SOM, and water holding capacity of sandy soils make it less fertile (Xie and Steinberger 2005). Suzuki et al. (2007) found higher soil moisture for crop growth in termite mound and bentonite treated soil. Soil treated with termite mound and bentonite showed an increase in clay and silt content. Clay soil has high CEC that promotes binding of positively charged nutrients, hence supporting crop growth and development (Hamarashid et al. 2010). In addition, organic matter binds well to clayey soil thus preventing from its rapid decomposition and increasing the soil water holding capacity (Lützow et al. 2006; Tahir and Marschner 2016). Tahir and Marschner (2016) found that the addition of clay in small peds to sandy soil increases the SOC sequestration and influences nutrient dynamics.

Breeders work with thousands of genotypes. Manual data collection for so many genotypes requires lot of resources. Involvement of unmanned aerial vehicle (UAV) can scan many genotypes in short time and these days low-cost UAVs are available in the market. These UAVs collect data in the form of reflectance at visible and near infrared (NIR) wavelengths. These reflectance values are further converted to different vegetation indices. Reflectance at two or more wavebands is used to compute vegetation index to detect vegetation difference among genotypes due to their morphophysiological properties (Huete et al. 2002). Normalized difference vegetation index (NDVI) is a commonly used vegetation index that is related to canopy greenness, leaf area index, plant biomass, etc., (Cabrera-Bosquet et al. 2011; Neiff et al. 2015; Tan et al. 2020). However, this NDVI is affected by several factors, soil background brightness being one of them. For a given amount of vegetation with exposed soil surface, darker soil substrates were found to overestimate NDVI (Huete et al. 1985; Huete 1988). Bausch (1993) found that dark color soil overestimates the basal crop coefficient for corn estimated from NDVI by 24% or more.

All these factors may affect crop growth and development. Genotypes planted in fine soil may perform differently than in coarse soil and soil may have variability in type, texture, color, moisture content, etc., at site or space level. Same genotypes planted in several replications may show differences.

15.3 Soil Heterogeneity Increases the Complexity of Agricultural Research

Variability of soil may also increase the complexity of agricultural research. Time is money. So, researchers prefer increasing the locations for variety testing than repeating the same experiment at same location for multiple years. However, increase in the number of locations may increase the complexity. This complexity comes from soil heterogeneity. Soils at different locations may vary in structure, texture, SOM, SOC, etc. This variability makes it difficult to test the varietal performance of crops by combining data from different locations. As a result, breeders go for the individual data analysis for each location. The major problem faced by breeders here is that a variety showing best performance at one location may not repeat the same at the other locations. Crop genotypes may show high performance at one environment but low stability. This slows down the process of selection and crop improvement. de Souza et al. (2020) conducted a multi-environment trial in 13 different environments. Same set of bean cultivars were planted in all the environments to test their adaptability and stability and the environments were categorized as favorable and unfavorable. The cultivars that performed better in favorable environments did not repeat the same in unfavorable environments and vice versa. Variation in adaptability of butternut squash, broccoli, and carrot varieties was observed at different organic production environments—Oregon, Washington, Wisconsin, and New York (Lyon et al. 2020). Some varieties showed broad adaptation while others were adapted to either high yielding or low yielding environments.

Soil variability also increases the complexity of decision-making for fertilizer or irrigation treatment. Uniform treatment of fertilizer or irrigation may result in toxic or under-availability water or nutrients in the soil at different sites on a field or research locations. It also affects crop yield and revenue earned from that crop. Site-specific management is needed to be precise in fertilizer treatment or irrigating the crops plant at different sites. Site-specific management is the field management concept that deals with adding inputs to the site based on existing variability. This triggers the need for location-specific study of soils for texture, structure, SOM, nutrients, etc. Zingore et al. (2007) selected a wealthy farmer's field and a poor farmer's field to study the influence of nutrient management on soil fertility and crop yield. Wealthy farmer used cattle manure that provided 36 kg N ha^{-1} and 10 kg P ha^{-1} to their farm, whereas poor farmer added little or no organic nutrients on their farm. The plots treated with manures in the wealthy farmer's field yielded 2.7–5 t ha^{-1} of maize grains, whereas the grain yield on poor farmer's field was 0.3–1.9 t ha^{-1}. This suggests how soil nutrient variability may influence the grain yield of same crops or genotypes differently at two different sites and hence, slow down the process of varietal selection by breeders. Li et al. (2001) conducted a landscape study in a center pivot irrigated field to study soil water distribution, soil N, cotton lint yield, and cotton N uptake in Texas. Soil volumetric water content, N uptake, and lint yield were higher on the lower landscape and lint yield was significantly positively correlated to soil volumetric water content ($r = 0.76$) and soil N ($r = 0.35$). This suggests that with the in-field variability in soil moisture and soil nutrients same experimental genotypes may perform differently.

15.4 Challenges in Exploring Soil Heterogeneity

Existing soil heterogeneity triggers the need for precision agriculture or site-specific management. Precision agriculture focuses on efficient use of resources for maximizing the productivity and profitability. Unfortunately, for efficient use of resources location-specific knowledge of soil must be known and studying this adds to additional expense for farmers and researchers. Another factor is lack of skills among farmers that makes this concept less popular.

There are several ways to do soil sampling for location-specific study. Random sampling is the simplest way to study soil variability. This method requires less knowledge to specify sampling sites and error is minimized in this process because of allocation of sites in a defined boundary. Randomly selecting the sampling sites is the representative of whole field. However, this process is complex and requires lot of resources. Chances are high that a researcher end up selecting most of the sites with minimum variability that might create biasness in data. To minimize this error, a large sample size is required but for large sample size, a large frame is need. In addition, this method involves manual collecting of soil samples by inserting tools in the ground. Increasing the sample size will be time taking and expensive. Once the samples are collected randomly, laboratory testing of each sample is done that involves extra expenses and time.

Another popular method is grid sampling. To minimize the cost, field consultants tend to increase the sampling grid size greater than 1 ha (Robert 2002). However, a previous study by Mallarino and Wittry (2000) indicates that increasing the sampling size from 0.4 to 1 ha provides inaccurate data for spatial nutrients demand.

Sensor-based methods are also used to study soil variability. EM38 (Geonics Limited, Mississauga, Ontario, Canada) is a proximal non-contact electromagnetic induction sensor used to assess soil variability based on apparent soil electrical conductivity (EC_a) (Doolittle et al. 1994; Sudduth et al. 2003). This equipment works best in an empty field or early growth stage of crops. Soil must be wet enough to provide accurate EC_a values. Using EC_a values obtained from EM38 survey, sites showing variability can be selected for soil sampling. However, soil sampling is followed by laboratory methods as explained above to determine soil texture, nutrients, etc., at different sites. This again is a time-taking procedure and requires resources.

15.5 Importance of Unmanned Aerial Vehicle in Detecting Soil Heterogeneity

Today UAV has gained much popularity among researchers. With the increase in production of low-cost UAVs, their ability to scan a large field in short time and collect near real-time data has made it a common tool to be used in research. From agronomic research to breeding to ecosystem sciences, UAV has made its place everywhere. Unlike satellites that have poor revisiting time and provide coarse spatial resolution (Moran et al. 1997; Stafford 2000), we can decide number of UAV flights per day based on weather condition and images obtained are of high spatial resolution. UAV can be a good tool to study soil heterogeneity. UAV mounted with thermal sensors can be used to map soil moisture variability over a large area (Gonzalez-Dugo et al. 2013). UAV mounted with thermal camera was flown at three different times in a day and stem water potential was measured during each flight. Irrigation was stopped prior to the flight date for some plots for soil water-deficit comparison. A clear-cut difference was observed between well-watered and water-deficit plots based on the difference between canopy (T_c) and air temperature (T_a). The difference was clearer at the mid-day when T_c-T_a was more negative for well-watered plots. In addition, slope of evolution of T_c-T_a from morning to mid-day correlated well with plant water status thus proving the influence of soil heterogeneity on plant's physiology. Baluja et al. (2012) used thermal and multispectral imagery to study the relationship between aerial temperatures/vegetation indices, leaf stomatal conductance (g_s), and stem water potential (Ψ_{stem}) in a vineyard field. A significant positive correlation of aerial temperature with g_s ($R^2 = 0.68$) and Ψ_{stem} ($R^2 = 0.50$) was observed. Similarly, NDVI showed a positive correlation with Ψ_{stem} ($R^2 = 0.68$). This suggests that soil moisture variability may affect plant water uptake and UAV can be used for assessing and mapping this variability.

UAV can also be used in determining variable fertilizer application. Vegetation indices derived from multispectral imagery was used by Lu et al. (2019) to determine the amount of N fertilizer application in winter wheat field. Images were collected from UAV at three different growth stages at seven view zenith angles - 0°, ±20°, ±40°, and ± 60°. Single-angle images showed highest accuracy for green chlorophyll index (CI_{green}) at −60° in estimating leaf nitrogen concentration ($R^2 = 0.71$) and at −40° in detecting plant nitrogen concentration ($R^2 = 0.36$). The accuracy of estimating plant nitrogen concentration improved by combining −40° and 0° images (red-edge chlorophyll index: $R^2 = 0.52$). UAV-based oblique images provided better estimation of plant nitrogen status and could be used to plan for a variable nitrogen application.

Overall, soil heterogeneity affects crop varietal growth and development, and UAV can be a great tool to study the same in variety testing programs.

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Environmental and Societal Implications of Soil Response to Increasing Agricultural Demands

16

Spencer Swan, Nicholas Hitsman, and Asim Biswas

Abstract

The world's population is growing at an exponential rate and is expected to reach over 9 billion by the year 2050. It is estimated that currently, nearly 2 billion people across the globe experience some form of food insecurity. The world's increasing population, plus those who already experience food insecurity highlight the need for agriculture to produce more food. There are different ways in which the food production goals can be met; however, with the world's climate crisis becoming more pressing, it is important that it be done in an environmentally sustainable way. Land use change and agricultural intensification are two common methods used to increase agricultural production. Land use change consists of the conversion of typically natural lands to agricultural uses. The process of land conversion can lead to adverse ecosystem effects such as the degradation of the soil resource, loss of far-reaching ecosystem services associated with forests and other natural landscapes, and an overall decrease in human and environmental health. Land intensification attempts to reach food production goals by increasing the productivity of land that is already used for agriculture. When managed properly these practices can lead to higher crop productivity while still being environmentally sustainable. However, when mismanaged they can pose serious threats to human and environmental health through the degradation of soil, air, and water quality. Land conversion and intensification are both helpful tools for increasing agricultural productivity;

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however, if they are not implemented with sustainability in mind, they can be of great detriment to the vitality of environmental and societal systems.

Keywords

Land use change · Intensification · Ecosystem health · Agricultural production

16.1 Introduction

Exponential population growth puts an immense strain on agricultural systems to produce more food which in turn impacts the soil resources, the base of agriculture. Experts project a population of 9 billion by the year 2050 (Prosekov and Ivanova 2018) with global demand for food increasing by 100–110% between 2005 and 2050 (Young 2020). Clearly, current agricultural systems will need to adapt to the increasing demand for food brought on by this rise in population. There are two ways that agricultural outputs can be increased. The first option is to simply convert more land for agricultural uses. This land use change has been effective in the past and in some developing nations because it increases the total land available for agriculture; however, many consider it to be unsustainable. The process of converting land from natural cover leads to the degradation of soil and the other ecosystem services provided by natural landscapes. For this reason, many consider the second option for improving agricultural yields to be the way for the future. This option is the intensification of existing agricultural practices, which consists of increasing the management effort and inputs into a field to achieve the highest yield possible. Agricultural intensification coincides with the concept of the Green Revolution, because this revolution brought with it several technologies which made intensification possible. Green Revolutions happen at different rates based on the development level of an area (Clay and Zimmerer 2020), but they all bring increased agricultural intensification. Traditional intensification methods consist of increased pesticide and fertilizer use, with increased sustainability being possible with consideration for the spatial and temporal aspects of their application. This consideration relates to the field of precision agriculture which will play a major role in sustainably increasing agricultural outputs in the future. While some intensification methods may be considered detrimental to the environment, proper intensification through the use of precision agriculture has the potential to greatly benefit agroecosystems (Bengochea Paz et al. 2020).

The soil resource is a crucial aspect of most natural ecosystems, but this is especially true of those found on or around agricultural land. The health and quality of soil surrounding agricultural practices not only leads to higher yields, it also aids in the prevention of the adverse side effects associated with agriculture. Some of the ecosystem services provided by soil include carbon sequestration, nitrogen fixation, and erosion control, which has a direct impact on runoff to aquatic ecosystems surrounding agricultural fields. Clearly, the sustainable use of soil should be a major focus of agricultural activities; however, both the processes of land conversion and intensification can be of detriment to this vital resource. The "sharing-sparing continuum" is a prime example of the debate between the merits of agricultural land's expansion versus intensification. The "land sharing" side argues that agricultural land should be expanded and managed at a low intensity so that natural and agricultural ecosystems may co-exist (Bengochea Paz et al. 2020). On the contrary, the "land sparing" side believes that smaller agricultural areas outputting at a high level is the most sustainable approach.

The act of converting natural landscapes for agricultural uses can influence the nutrient dynamics of a soil, which can lead to negative consequences for the environment and subsequently human populations. For example, soil is a crucial part of the global carbon cycle, acting as either a sink or source of atmospheric carbon, depending on its management. As a sink, the soil, or pedosphere, contains three and four times as much carbon as the atmosphere and biosphere, respectively (Lal 2004). Clearly, the release of this soil organic carbon (SOC) through the mismanagement of our soil resources would be of great detriment to the environment and the people who depend on it. Ultimately, the pressure faced by the agricultural sector from rapidly increasing population numbers requires a great deal of attention in the form of increased agricultural outputs. There are advantages and disadvantages to both the land conversion, and the intensification methods for achieving this increase. Given the magnitude of the issue and mankind's dependence on our soil resource, great care must be taken in the management of this heightened agricultural activity. This chapter will examine both land conversion and intensification and their implications for managing soil resources for the betterment of human populations and the environment.

16.2 Land Conversion

Land conversion has been an effective method for increasing agricultural outputs in the past; however, its losing popularity given the limitations of its continued practice. Agricultural land conversion is destructive and self-limiting because it leads to the degradation of the soil resources which it relies on most. For example, Bengochea Paz et al. (2020) highlight a positive feedback loop that exists between human populations and agricultural production. They explain that as agricultural production increases through land conversion, human populations can grow because of increased availability of food. This leads to the need to convert more land for agricultural uses, which further degrades the agroecosystem and results in negative impacts on human populations (Bengochea Paz et al. 2020). This degradation feedback loop (Fig. 16.1) highlights the impermanence of land conversion for the sustainable increase of agricultural outputs given its impact on both environmental and human health.

Different land uses lead to different nutrient dynamics in the soil, meaning that converting land for agricultural uses has the potential to negatively impact soil

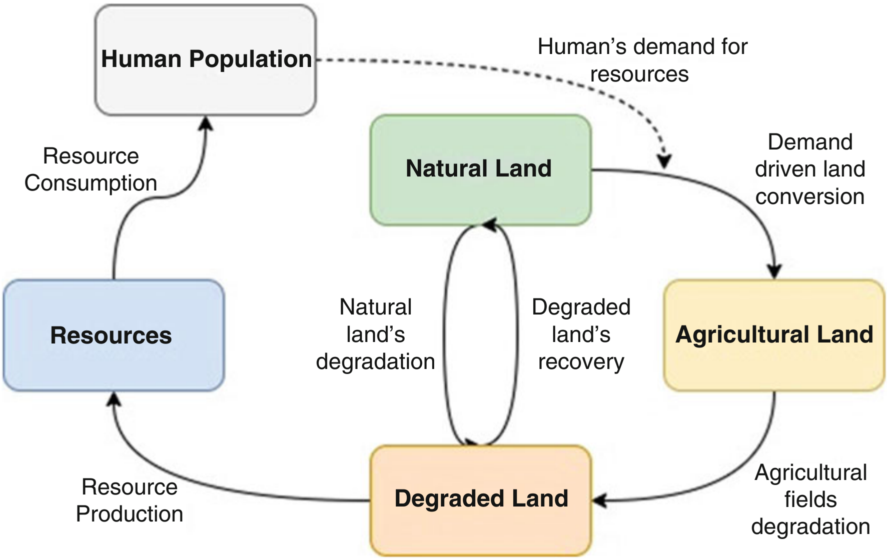

Fig. 16.1 Graphical depiction of degradation feedback loop adapted from Bengochea Paz et al. (2020)

health. Given the importance of the issue, several studies have been conducted to assess the impact land conversion has on soil nutrients. One such study by Cerri et al. (2007) aimed to project the effect that land use change has on soil organic carbon (SOC) stocks in the Brazilian Amazon. The researchers looked at the period from 2000 to 2030 using a variety of methods and under various scenarios and found that SOC declined following conversion from native vegetation in all of them (Cerri et al. 2007). More specifically, one projected deforestation scenario used in the study estimated that roughly 4200 teragrams (Tg) of carbon would be lost by 2030 compared to stocks from 1990 (Cerri et al. 2007). Adding to this loss of SOC would be the carbon lost due to reductions in biomass following deforestation, which enters the atmosphere in the form of CO_2 (Cerri et al. 2007). Ultimately, the effects of deforestation for agricultural purposes highlight the need for effective management of land resources for the continued vitality of soil and the environment.

Soil carbon is not the only important nutrient impacted by land use conversion for agricultural purposes. Stocks of soil nitrogen and phosphorus, both also indicators of soil health, can experience adverse effects following conversion to unsustainable land uses. Wong et al. (2020) compared the physicochemical properties of Malaysian soils on naturally forested sites with that of rubber and palm plantations. They found that both soil carbon and nitrogen levels were the highest in the naturally forested sites, and lowest in the two agricultural ones (Wong et al. 2020). Like Cerri et al. (2007), these researchers found deforestation for agricultural purposes to lead to the soil leaching nutrients into the environment as a result of its overall poorer health. Similarly, Franco et al. (2015) conducted a study in Brazil where they examined nutrient dynamics under natural, pasture, and arable land uses. They found that converting from native vegetation to pasture led to a decrease in soil organic matter (SOM), with net carbon emissions of 0.4 Mg ha^{-1} $yr.^{-1}$(Franco et al. 2015). Unsurprisingly, the researchers reported even higher carbon emissions following conversion to sugarcane crop at a rate of 1.3 Mg ha^{-1} $yr.^{-1}$, with a 40% and 35% reduction in carbon and nitrogen soil stocks, respectively (Franco et al. 2015). These increased carbon emissions pose even more danger to the environment and human populations given that they are a result of the removal of trees, meaning there is less potential for carbon sequestration to filter the released greenhouse gases from the atmosphere. Evidently, any conversion from natural land uses will result in adverse effects to soil nutrient dynamics, but clearly the increased management effort associated with conversion to arable land presents the greatest threat to soil health.

While land conversion's impacts on the pedosphere are numerous and much more obvious, hydraulic regimes also face adverse effects following land use change. With trees playing such an important role in ecosystems, it follows logically that their removal through deforestation would greatly impact several ecosystem functions. One of the major impacts felt by human populations and the environment following deforestation is increased severity and frequency of flooding events. The elevated levels of surface water runoff associated with these floods are a function of the lower levels of water infiltration and increased soil densities which stem from deforestation (Merten et al. 2020). These floods further damage human populations by way of decreasing arable land available for the proliferation of agriculture (Merten et al. 2020), suggesting a similar feedback loop to the one mentioned earlier. Continuing the topic of agriculture's influence on surface water, dam construction for irrigation to fuel agriculture has also been shown to have adverse effects on the hydrology of an area. For example, Mirzaei et al. (2020) performed a case study on the Aras River in Turkey and found a compounding effect of upstream dam construction leading to decreased water availability for drinking water, industrial and agricultural uses downstream. Humans are not the only ones to suffer the effects of wide scale diversion of water flow, the impacts reverberate throughout the entire aquatic ecosystem with the potential for complete ecosystem devastation. This study highlights the potentially wide-reaching impacts of land conversion and its indirect impacts, and the obvious need for careful planning around ways to increase agricultural production while avoiding some of the negative side effects associated with land use change.

The more obvious disturbances to hydraulic regimes following agricultural land conversion are significant, but the less visible hydraulic properties of soil are also threatened by the processes associated with land use change. In a 2020 study by Bush et al. comparing soil physical and hydraulic properties at forested and pasture sites, there was a significant difference found between the saturated hydraulic conductivities and bulk densities of the soils at the two sites. They also found that the ratio of overland flow to rainfall was higher at the deforested sites, suggesting decreased infiltration of water (Bush et al. 2020). Clearly, deforestation is detrimental to hydraulic aspects of soil health at both a landscape and microscopic level and has implications on human and environmental health which must be mitigated.

When it comes to sustainably converting land for agricultural uses there are not many options other than simply not doing it or doing less of it. There is, however, the concept of agroforestry which can achieve some of the desired effects of land use change while mitigating the less desirable effects on ecosystem and soil health. Agricultural operations performing agroforestry will clear land for agricultural use, while keeping a significant number of trees on the workable land. By mixing land uses, agroforestry allows farmers to reduce nutrient loss associated with deforestation, slow the runoff of excess nutrients to surrounding water bodies, and maintain the carbon sequestration potential of their land as well as several other ecosystem services provided by trees. While it may seem like dedicating sections of agricultural fields to forested land uses might decrease the short-term productivity of fields, despite the long-term benefit, the opposite can be true. A study by (Nyberg et al. 2020) examining the use of sustainable agricultural practices in Kenya's Agricultural Carbon Project found agroforestry to improve maize yield. This comes as little surprise given the many ecosystem services provided by trees and how they benefit the soil resource that agriculture relies so heavily on. Another potential method for sustainably increasing agricultural outputs without completely discarding land conversion as an option is intercropping. Intercropping refers to the planting of multiple crops on a single plot of land in order to take full advantage of the climatic conditions of an area which a single crop might not accomplish. While intercropping is certainly an effective method for getting the most out of agricultural land, great care should be taken in its planning and management as it can easily contribute to the degradation of soil and ecosystem health. In essence, land conversion is no longer an ideal option for feeding a growing population, but there are instances where it can be done with sustainability in mind.

Ultimately, achieving increased agricultural production via land conversion has its limitations given the ever-increasing population needing to be fed and the finite land and soil resources available to us. First, agricultural land conversion to feed growing populations leads to a positive feedback loop which causes it to be self-limiting in nature. Additionally, the change from natural land uses such as forest and grassland has the potential to greatly impact nutrient dynamics in the soil. Soil carbon and nitrogen stocks decrease in the face of agricultural land conversion, leading to increased outputs of these nutrients into the environment and poorer overall soil health. These impacts have implications for human populations in the form of increased contribution to global climate change, as well as decreased soil health leading to greater potential for food scarcity. In essence, land conversion will inevitably play a role in the quest to increase global food production, but its role should be limited and well managed, in order to minimize the impacts on environmental and human health.

16.3 Land Intensification

Intensive agriculture is leading to many adverse effects on environmental and human health. These adverse effects can come in the form of reduced soil, air, and water quality. Although agricultural intensification is necessary to produce more food as the world's population increases exponential, it is important to also consider how these practices may affect both environmental and human health. These adverse effects can be minimized through land management practices used to mitigate problems such as excessive fertilizer application which pollutes the planets water and air, tillage practices which release CO_2 from the soil into the atmosphere, and monocropping which can leave soil susceptible to erosion and nutrient loss. The term "Sustainable Intensification" is now being used to describe the necessary changes needed in the field of agriculture to meet both crop production and sustainability goals (Rudel 2020; Pretty 2018). Industrial farming and intensive agriculture have various effects on soil health. Practices such as monocropping, tillage, and fertilizer use all have adverse effects on soil health. Monocropping, which is the practice of planting the same crop year after year, depletes the soil of nutrients, and can cause structural damage to the soil leaving it susceptible to erosion. Going forward it is important to include crop rotation into agriculture practice, as this practice can reduce the risk of erosion and increase the nutrient availability in the soil.

Conventional tillage practices, often used to increase crop production, can have several adverse effects on soil health. For example, conventional practices can disrupt soil aggregates, making them smaller, which leaves the soil more exposed to erosion and nutrient loss processes (Baulch et al. 2019). This can lead to a wide variety of problems including nutrient runoff and water pollution, reduced land productivity, and reduced soil organic carbon content. The implementation of conservation/no-till practices can help promote soil health by increasing soil aggregate stability, and increasing soil organic carbon, leading to more productive land, and reduced erosion risk and nutrient runoff.

Repeated and excessive fertilizer application can also pose a risk to soil health. Phosphate fertilizers and animal manure both have heavy metals such as Cadmium, Arsenic, and Chromium among others found in them, which with repeated application can build up in the soil (Mortvedt 1995). This poses a risk to the environment as well as humans, as the heavy metals in the soils can accumulate plants, which are then harvested for consumption, meaning these heavy metals could eventually be ingested by humans, which can lead to numerous health risks such as neurological degenerative processes, and can lead to diseases such as Parkinson's and Alzheimer's (Jaishankar et al. 2014).

Intensive agriculture can impact local air quality in various ways. Conventional tillage and plowing methods can disrupt the soil and expose the carbon within the soil to oxygen in the air (Rutowska et al. 2018). The carbon and oxygen then combine to form CO_2 which enters the atmosphere here and can result in reduced air quality. These CO_2 emissions are large contributors to climate change, and reduced air quality. Tillage and field plowing both have large effects on soil carbon.

Krauss et al. (2017) compared the effects that conventional and reduced tillage has on soil carbon in temperate climates. It was found that conventional tillage reduced the soil organic carbon stocks in the top 0.5 m of the soil compared to reduced tillage practices (in an organic grass-clover ley-winter wheat cropping sequence). Reduced soil organic stocks mean that carbon has become oxidized after being tilled and contributes to the atmospheric CO_2 emissions. Conservation tillage practices disrupt the pore class distribution less than conventional practices, which is important characteristic when it comes to the carbon oxidization/emission process (Reicosky 1997; Oliveira Silva et al. 2019). Fuel consumption/emissions also must be considered when evaluating how intensive agriculture effects environmental and human health. Tilling fields and the application of fertilizer/pesticides requires tractors, which consuming fuel and produce CO_2 emissions. Although this may seem like a small issue, when numerous industrial farms are all tilling fields or applying fertilizer or pesticides, the fuel consumption and emission can become a problem in terms of air quality. When comparing fuel consumption and CO_2 emissions for conventional and no-till systems, it was found that nearly 5x the amount of fuel was consumed under conventional tillage practices, and 145.57 kg CO_2/hectare produced in conventionally tilled systems compared to the 37.42 kg CO_2/hectare produced in no-till systems (Antmen 2019).

Air pollution from agriculture practices can affect human healthy both directly and indirectly. The CO_2 released from tillage practices and running machinery can have local effects, such as reduced air quality. This can lead to several human health related problems such as respiratory issues such as lung disease and breathing problems. Indirectly, agriculture practices contribute to climate change which can leave communities more susceptible to extreme weather events, such as flooding, putting people's livelihoods at stake. To address these problems more sustainable agriculture practices have been implemented in recent years, such as conservation/no-till cropping systems to reduce soil carbon loss and reduce fuel consumption. Precision agriculture has also played an important role in terms of reducing the impacts that fertilizer has on human health and the environment.

Agricultural intensification in many cases has adverse effects on natural water systems within the area. These problems primarily arise from nutrient runoff/leaching. The excessive application of fertilizers to agricultural lands is a primary cause of aquatic pollution in natural waters surrounded by agricultural lands. Inefficient use of fertilizers can lead to a less than optimal trade-off between crop production and environmental harm. Nitrogen is often a limiting factor for crop production, which can lead to the over application of nitrogen fertilizer. When over applied, there is excess nitrogen which is not used by the plants. This excess nitrogen can then make its way into ground water, and lead to eutrophication (Harrison et al. 2019).

The adverse effects that intensive agriculture have on the environment can also impact human health. Nutrient leaching into water systems can impact human health in several ways including the pollution of drinking water and reducing community's ecotourism. Several examples of this can be seen across North America. In 2014, Toledo, Ohio had to shut off their drinking water supply due to harmful algal blooms that we caused by the eutrophication of lake Eerie, due to high amounts of nutrient loss from agricultural lands (Bernado et al. 2017).

Accurate and timely fertilizer application is also necessary to ensure optimal crop growth and reduced environmental damage. Precision agriculture can help in doing this through the use of remote sensing. Remote sensing can provide valuable information on certain characteristics of land such as topography and hydrology which are important factors when determining fertilizer timing and application rates (Sishodia et al. 2020). Precision agriculture can be used to identify the optimal application rate of fertilizer, known as a fertilizer target, to ensure increased crop production while at the same reducing the harmful effects that over application of fertilizer has on the environment (Vogeler et al. 2020).

16.4 Summary

Exponential global population growth has driven the need for a sustainable increase in agricultural food production. The two methods for achieving this increase; land conversion and agricultural intensification each have their own implications and variables affecting their overall sustainability. In general, converting land for agricultural uses is an unsustainable and self-limiting practice which achieved sparse success in the past, but has little place in the modern day given the ever-decreasing land available for agriculture. Land use change has the potential to lead to the degradation of soil resources, which has compounding effects on environmental and human health. The unchecked expansion of agricultural practices not only leads to the eventual depletion of soil nutrients, but it increases the release of those nutrients to both the atmosphere and nearby water bodies from the soil. Additionally, the removal of trees results in the decreased carbon sequestration potential of an area, as well as the soil's ability to filter pollutants from water, leading to a doubling effect of unwanted nutrients entering the ecosystem. The adverse impacts that land conversion has on hydraulic regimes should not be ignored, with both above and below ground flow being affected. Overland flows of water are impacted as a result of decreased water infiltration and dam construction for water to fuel agriculture and the effect are far reaching to both human populations and the environment. In addition to the hydraulic regimes of a soil, its hydraulic properties such as hydraulic conductivity can be affected by land conversion, further evidence of the scope of damage done by converting natural lands to agricultural uses. While land conversion is certainly not a popular option for the objective of increasing food production, there are ways it can be done relatively sustainably. One such way is through agroforestry, which incorporates trees into the agricultural landscape so that their ecosystem services are not lost following agricultural expansion. This method has been shown to be effective for decreasing the adverse effects agriculture can have on nearby ecosystems and even has the potential to increase agricultural yields. Another way to sustainably increase agricultural production in the scope of land conversion is to utilize intercropping in order to maximize the growing potential of the soil. However, great care should be taken with this approach because the threshold of overexploitation of the soil is very easy to breach with this practice. Ultimately, land conversion has had its place in feeding the worlds populations in the past, but with the issues faced by today's agricultural systems, sustainable intensification seems to be the only way forward.

Agricultural intensification can be an effective and sustainable way to meet the worlds increasing food demand. Intensive agriculture can have numerous adverse effects on both environmental and human health. Practices to increase crop productivity such as fertilizer application, tillage practices, and pesticide use all can have harmful side effects impacting both the local and global health of humans and the environment. When using these practices to increase crop production it is important to use all the information, technology, and management systems available to not only increase crop production but to increase the sustainability of agricultural practices as well. Precision agriculture can be a useful tool to determine accurate and timely application of fertilizers and pesticide in order to promote crop productivity and minimize the environmental/human health risks they may pose. Conservation agriculture can also be useful in tillage practices, as they can help reduce the strain and impacts that traditional agriculture has on soil properties, such as its ability to act as a carbon sink, which is becoming ever more important as the global climate continues to warm. All in all, agricultural intensification has its pros and cons, but if managed properly, it can help the world reach its food production goals, while also reducing the environmental footprint agriculture has had for decades and can contribute to an overall healthier population by reducing the health risks it causes for humans.

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Part II

Recent Scientific Advances Covering Broader Aspect of Natural Resource Management

Soil-Centric Approaches Towards Climate-Resilient Agriculture

17

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Abstract

Soil-centric approaches mainly focus on management of soil for the improvement of soil organic carbon (SOC) which plays a major role in sustaining the soil fertility vis-a-vis productivity. This kind of approach is the need of the hour particularly in the tropics and sub-tropics where the soil having very low amount of soil organic carbon (SOC) even less than 0.5% only. The main pillars of soil-centric approach are conservation agriculture, no-tillage system, using cover crops and mulching. All these can play very crucial roles in increasing the SOC when applied for long-term basis. Changing climatic scenario has great influence on soil formation as well as soil fertility. Such as elevated CO_2 level in the soil as well as raise in the soil temperature largely manipulate the soil micro-biome and availability of nutrients to the plants. Thus, under this situation, the importance of adopting soil-centric approaches is massive to maintain the sustainability in the agricultural production system. Carbon sequestration is very important aspect under soil-centric approach. This is crucial to mitigate climate change as well as improving the soil as a whole. Both the above ground and below ground carbon sequestration are very much crucial to maintain the carbon-cycle and reducing the

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adverse impact of climate change caused by elevated CO_2 level in the atmosphere. Soil-centric approach ensures the lockdown of carbon in belowground condition more than other soil management approaches. In this chapter, efforts have been made to elaborate the concepts of soil-centric approaches and their importance under changing climatic scenario.

17.1 Introduction

Soil is a living body contains numerous macro and microorganisms, essential plant nutrients, water, air, etc. (Fortuna 2012). Success of agriculture largely depends on soil. If soil is barren or non-fertile specifically non-productive, planning of agriculture is not even possible. On the other hand, formation of soil from the rock is not at all a short procedure. It takes millions of years to form a thin layer of soil from rock (Hillel 2008). Thus, any approaches in our agriculture must be soil-centric. Unfortunately, sometimes we forget the values of the soil and its parameters of fertility focusing only on higher productivity with the maximum exploitation of the soil. It creates a havoc loss in the soil fertility and sustainability which is a major threat to the agriculture these days. A fertile soil should contain about 4% organic carbon (SOC) as per the World Food Prize, 2020 laureate Dr. R. Lal (The Indian Express 2020). However, most of the soil across the globe contains much lesser than that. The picture concerning SOC in sub-tropical and tropical countries is very alarming as the turnover of soil organic carbon to CO_2 is very rapid in these areas. FAO, United Nations also stated that almost one third of the soil on planet is "moderately to highly degraded" (FAO and ITPS 2015). This is mainly because of the continuous soil erosion process through wind and water as well as unscientific and irresponsible unsustainable agricultural operations. In India, the picture is more terrifying. We have continuously losing the SOC. Some part of the country even witnessed the SOC level of less than 0.5%. When SOC has become less than the buffering capacity of the soil, soil microbial activities which majorly control the nutrient availability, will be very low leaving the soil unsuitable for agriculture (Neina 2019). So, automatically the living soil will die and this phenomenon is a great threat to the mankind. Productivity increment is an obvious need of the hour to feed the ever-growing population on the earth. But, such increment degrading natural resources and soil in particular is very much fatal. So, soil-centric approaches are much now-a-days.

Soil-centric approaches majorly focus on the improving the SOC by different means without depleting the productivity of the crop. SOC can be increased by different approaches like using organic manures, mulching, adopting the conservation agricultures, cover crops, crop rotational approaches, inclusion of leguminous crops, etc. Continuous application of reduced tillage in diversified rice-based cropping system in eastern India has shown a considerable increase in the SOC. This practice also improves the soil microbial activities to a considerable extent than the conventional agricultural practices (Kar et al. 2021). Haddaway et al. (2016) reported that adoption of no-till system under conservation agriculture can mitigate the climate change and improve the soil health as considerable C-storage in the soil can be achieved through these practices. Based on their study, no-till increased the SOC of the top soil (0–30 cm) around 4.6 Mg ha^{-1} over conventional tillage in 10 years. Such higher SOC in the top soil would be very much beneficial for the soil biological activities, nutrient mobilization and availability which ultimately improved the yield of the crops (Kar et al. 2021). Swanepoel et al. (2018) stated that conservation agricultural practices could improve the conditions of the farmers by improving soil health which ultimately reflected through the better productivity with superior quality. However, these practices are largely depending on local weather as well as soil situations.

Thus, the adoption of soil-centric approaches in agriculture is very much beneficial than the conventional management of agricultural systems. Specifically, by adopting the various approaches considering soil as a whole living body would be very much advantageous in reducing cultivation cost, escalating physical, chemical as well as biological properties of soil and thereby augmenting the overall productivity of the agricultural system by making it sustainable (Triplett and Dick 2008; Verhulst et al. 2010; Zarea 2010; Rakshit et al. 2017). However, there is number of concerns to the soil-centric approaches which must be addressed suitability as well. In particular, site-specific soil-centric approach development is also a needful task to the researchers in the field of agriculture. Soil-centric approaches should be different for temperate and tropical or sub-tropical climatic conditions. Furthermore, the preferences of the farmers must not be forgotten as any concept will be successful when that concept will be well-spread to the ultimate used of the technology, the farmers. Several policy interventions from the government levels also demanded highly. The right of the soil must be reserved as the rights of the human being. In this chapter, we have tried to highlight the concept of soil-centric approaches and its different dimensions with special reference to its importance under changing climatic scenario particularly in Indian subcontinent.

17.2 Impact of Climate Change on Soil

Climate has been changing since the existence of the earth. However, the changes are rapid during last 50–100 years. Hence, it creates huge concerns and most debatable topics to the scientists and policy makers recent times. The impacts of climate change on the soil are enormous. Quality and productive soils have become very top priority even more before earlier times since food security and sustainability in production comes into the top-most concern. Tropical countries like India and its neighbouring countries are very much susceptible to soil degradation due to climate change owing to having high temperature demand and poor coping capability of the farmers. Even though, changing of climate is relatively slow process, these slow processes have enormous impact on the soil formation and maintaining soil fertility (Pareek 2017). Changes in soil moisture lever, increase in soil ambient temperature as well as CO_2 in the soil are the most probable effects of changing climatic scenario on soil ecosystems.

17.2.1 Soil Formation and Development

Both the precipitation and temperature have the major control on soil formation. These two climatic parameters are majorly responsible for weathering of rocks and formation of biomass that helps in soil formations. Summation of active temperature as well as ratio of rainfall and evaporation mainly decides the amount of energy required for soil formation, water-balance in the soil, proportion of organic matter and minerals in soil, etc. Continuous increase in temperature causes irreversible changes in mineral matrix of soils. Moreover, climate change increases the soil--mineral-destruction energy and this phenomenon will be responsible for the simplification of mineral matrix (Pareek 2017). At the same time, soil biological, hydrological activities will also be changed under such changing climatic scenario. All these ultimately influence the soil formation process negatively resulting in loss of soil fertility vis-a-vis productivity (Karmakar et al. 2016). Climate, nature of vegetation, and types of parent materials are the major controlling agents for soil development. Climate change has direct effect on these three major agents. Increase in temperature, elevation of CO_2, and changes in precipitation largely influence the vegetation types, soil moisture levels. Climate also plays a pivotal role in weathering of parent rocks to form soil. Changes in the climate through altering temperature and rainfall pattern also impact on weathering process which ultimately resulting in mineralogical and chemical changes in the rock. Thus, under different climatic conditions, the similar type of rock mineral will show changes in the soil properties.

17.2.2 Soil Fertility and Productivity

Soil formation and development are largely influenced by the climate change. So, the factors of climate change will definitely influence the soil fertility as well as productivity. However, these effects are very much region specific in nature. The impact of climate change on deferent soil fertility parameters is described in Table 17.1.

Table 17.1 Impact of climate change on various soil processes

Parameters of climate change	Impact on soil processes
Increase in temperature	Reduction in LSOMp (labile soil organic matter pool)
	Reduction in SOM, soil moisture
	Increase in soil-respiration, rate of mineralization
Elevated CO_2 level	More soil C to the soil-micro organisms
	Accelerated nutrient recycling
	Increase in soil water

17.2.3 Nutrient Transformation in Soil

Plants uptake essential nutrients for their growth and development from the soil solution where the nutrients must be in mobile form. Soil moisture and temperature have strong influences on biological changes between inorganic and organic pools in soil solution. Increase in the temperature in the soil solution will increase the rate of N-mineralization leading to increased concentration of N into the soil solution. However, elevation of CO_2 level has no direct effect in this aspect (Pendall et al. 2004). Increase in the soil temperature and changes in the moisture level in the soil owing to having climate change will influence the adsorption or desorption reaction rates and ion status into the soil.

17.2.4 Soil Carbon Dynamics

Increase in the CO_2 concentration in the soil will stimulate the soil microbial activities which will reduce the nitrogen availability in the soil. It is a well-known fact that escalation in the soil CO_2 levels alters the status of root-derived compounds. On the other hand, more microbial activities cause more CO_2 release and such phenomenon will pursue negative impact on soil organic carbon dynamics. Several previous studies using C isotope tracers demonstrated that the production of CO_2 in the rhizosphere by roots and microorganisms is significantly stimulated by elevated CO_2 plant growth conditions. The stimulation of CO_2 respiration in the rhizosphere may be much higher than the enhancement of root biomass. Cheng and Johnson (1998) demonstrated that although plants produced only 15–26% more biomass under elevated CO_2, rhizosphere respired C increased by 56–74% as compared to ambient CO_2 treatments.

17.2.5 Response to Mycorrhizal Association

The population of the soil mycorrhizal community is elevated with the increase in the concentration of the soil CO_2 concentration. This is because of the increment in the demands of plant nutrients coupled with augmentation in the carbon assimilation owing to having high concentration of CO_2 in the soil. Plant demands for N and P will increase concurrently with C assimilation rates, and plants will allocate more photosynthates below ground to the roots and mycorrhizal fungi to help satisfy this increased nutrient demand (Drigo et al. 2008). Thus, under higher CO_2 concentration the P-uptake by plant roots will be increased (Pareek 2017).

17.2.6 Soil Biological Activities

The soil microbial activity under elevated CO_2 levels in the soil is variable and it is very important for the nutrient availability point of view. Changes in the microbial community, nitrogen mineralization as well as immobilization, etc. are wide varied under increased CO_2 level in soil. Soil microbes are facing the C-limitation more often. Hence, increased C-level in the soil will stimulate their activity. In general, it is believed that C-availability in the soil will be increased under CO_2 elevated soil and this phenomenon will stimulate more fungal growth than bacterial activity. Thus, the elevated CO_2 level in the soil has strong influence on soil functioning indirectly as fungi are known to play pivotal roles in the degradation of soil organic matter, recycling of plant nutrients, and the formation of soil aggregates. Moreover, under elevated CO_2 levels, C/N ratio in the soil will be increased which means the lower availability of N in the soil (Hu et al. 2001). And this phenomenon again justifies the abundance of fungal biomass over bacterial biomass as the fungi have lower N demand than that of bacteria. Both fungi and bacteria are the substrates for various grazers in soil food web which will help in rapid nutrient recycling as well as nutrient flux in the soil. Thus, increase in the microbial biomass under elevated CO_2 level in the soil will be helpful in improving soil nutrient status.

17.3 Concept, Principles, and Characteristics of Soil-Centric Approaches

Soil-centric approach majorly conceptualized as the management of soil concerning its health which is majorly governed by the soil organic carbon. Soil centric approach is focuses on the replacement of the nutrients which are removed by different agricultural operations. Such approach also responds wisely about the changes occurred in the soil due to long term agricultural practices and predicts of the future phenomenon which is going to happen from anthropogenic and natural perturbations. This concept encourages the agricultural management on soil-based rather soil-resilient, ecosystem-based which ensures eco-efficiency and knowledge based, precisely science and management driven approach. Under soil-centric approach, the efficiency of the nutrient use is the utmost important. Acquiring the higher input-use efficiency is the major goal in this approach. More often, we describe the soil fertility in terms of nitrogen, phosphorus, and potassium (NPK) status of the soil. However, under soil-centric approach, the soil fertility indicator is not only NPK but CNPK (carbon, nitrogen, phosphorus, and potassium). The basic principles of the soil-centric approach are described below.

17.3.1 Principles of Soil-Centric Approaches

17.3.1.1 Conservation Agriculture Practices

Conservation agriculture might play a very important role in the improvement in the SOC as well as regeneration of the soil. Several studies across the globe reported that the long-term zero-tillage or no-tillage crop management strategy could escalate the SOC to a considerable extent. No-till and crop cover farming are the important conservation agricultural practices which focuses on improving soil health and reducing the environmental impact of farming. Kar et al. (2021) showed that conservation and reduced tillage system improved the SOC content as well as the physical health of the soil. They also reported that reduced tillage system improved nutrient use as well as recovery efficiency besides augmenting the overall system productivity and production efficiency of different rice-based cropping systems in eastern India. Busari et al. (2015) also depicted that conservation tillage practices improved the soil physical, chemical, and biological properties which provided better nutrient availability in the soil and escalated the nutrient uptake by the plant. Thus, higher nutrient recovery could be attained.

17.3.1.2 Covering the Soil with Mulches and Plant Debris

This will keep the soil cooler and prevent the heavy rains from washing away the top-most fertile soil layer. This practice has immense importance in regenerating the soil as well as recycling the soil nutrients. Loss of the top-most soil through erosion is the very alarming condition faced by almost every corner of the globe particularly in the tropic and sub-tropics. It takes millions of year to form soil form parent rock minerals. Thus, losing the fertile soil layer will create huge problem in the near future to practice agriculture. Covering the soil with mulches has multifarious benefits like conservation of soil moisture, nutrient, encouraging soil microbial biomasses. All these are basis for soil-centric approaches. Singh et al. (2021) reported that mulching can improve nutrient uptake, productivity, water vis-a-vis nutrient budgeting of the filed mustard. Highly positive correlation between SOC content in the soil and long-term impact of thicker layer mulching (10 cm) was found by Bajorienė et al. (2013). From the experiment on "The impact of mulch type on soil organic carbon and nitrogen pools in a sloping site," Bai et al. (2014) showed that application of forest mulch for 5 years significantly influenced the soil fertility and reduced the erosion of the top-most soil layer.

17.3.1.3 Application of the Crop Cover

This is a unique concept where the crops are grown and not harvested and they were allowed to complete their life cycle in the field. The nutrients borrowed by these cover crops for their growth and development will be returned to the soil after the decomposition of these plants into the soil. There are many benefits of using cover crops in agriculture. They are useful to reduce soil erosion by creating natural mulching on soil surface. Besides improving soil fertility by augmenting the soil micro-biome as well as SOC, the cover crops are beneficial in improving soil moisture status, control of weeds, etc. The cover crops mainly consist of various legumes primarily improve the ecological services by escalating the carbon sequestration and regenerating the soil fertility. Even, under more climatic stresses, the cover crops are playing a key role in soil-centric approaches. Sharma et al. (2018) reported that the cover crops are the pivotal player to restore the soil organic carbon as well as the soil micro-biome under changing climatic scenario. Use of leguminous cover crops is one of the major adaptation strategies under climate change. They also expressed that long-term use cover crops are helpful in increasing the availability of macro vis-a-vis micro nutrients like K, Mg, Fe, etc. in the soil.

17.4 Soil Carbon Sequestration

The word sequestration means impounding, thus, carbon sequestration (C-sequestration) can be stated as the method or mechanism of storing/capturing atmospheric carbon. This is considered as one of the most important issues to reduce the global warming potential (GWP). The concentration of CO_2 in the atmosphere is increasing at a rate of 0.6 ± 1 ppm year^{-1} and recently the concentration is about 409.8 ppm (NOAA 2020). The afore-mentioned data clearly indicate the importance of removal or capture or impounding of the atmospheric C present as CO_2. In this chapter, we are trying to enlighten the mechanism of C-sequestration and the different aspects of this method under agroforestry systems.

17.4.1 Importance of Soil Organic Carbon

Soil organic carbon (SOC) is derived from living tissue such as plant leaves and roots, sap and exudates, microbes, fungi, and animals (Khatoon et al. 2017). SOC consists of mystifying varieties of varied complex-chemical forms of which many are yet to be classified. All these forms are formed owing to decaying of the living materials. Soil organic matter (SOM) is a generic or common name containing about 50–58% of C on dry weight basis (Menichetti et al. 2019). SOM is the critical component to form soil aggregates giving stability to the soil against erosion loss and weathering. It is also playing the crucial role in holding soil moisture and essential soil micro-biome (Blaud et al. 2017). Many forms of SOM can be readily oxidized (turned into carbon dioxide) by common bacteria in the presence of oxygen. But it is also the form of soil carbon that can readily increase because of plant growth, the root shedding of perennial grasses, the incorporation of manure or compost, the liquid carbohydrate exudates of plant roots, all processed by microbial metabolisms. Soil organic matter is the most abundant form of soil carbon (Johns 2017).

17.4.2 Mechanism of C-sequestration

C-sequestration process clearly demonstrates the long-term lockdown of C into plant or animals. Such sequestration has immense importance of reducing the immediate convert of C to CO_2, thereby, reducing the GWP to a considerable extent. Burning of fossil fuels to fulfil the demand of modern day human activities resulted in the release of huge amount of C in the form of CO_2 and destroying the long-term storage of C in the form of petroleum, natural gas, coal, etc., however, CO_2 is emitted through the process of plant and animal debris-decomposition as well. But, the volume of such emission is much lesser than the day-by-day increase in CO_2 release through fossil-fuel-burning owing to anthropological needs. C-sink is considered as the pool keeping C into them, thus, restricting the release of C in the form of CO_2 into the atmosphere. For instance, planting trees or afforestation is one of the importance means of C-sink, while, reducing the forest land to dwellings is the prominent example of encouraging the C-emission process into the atmosphere. To understand the mechanism of C-sequestration, the understating of C-cycle is very crucial. Transformation of the Carbon is taken place in different modes in the atmosphere and the hydrosphere. Formation of H_2CO_3, HCO_3^-, and CO_3^{2-} are the major way to replace CO_2 from the atmosphere and the oceans. Mollusk shells or mineral precipitates that formed by the reaction of calcium or other metal ions with carbonate may become buried in geologic strata and eventually release CO_2 through volcanic outgassing (Britannica, 2019). CO_2 also exchanges between plants and animals in the means of photosynthesis and respiration. After decomposing of organic matter produced from dead plant or animal emits CO_2 or CH_4 into the atmosphere or these may form fossil fuels. Again the burning of these fossil fuels released CO_2 to the atmosphere. The biological pathways involving photosynthesis or respiration are rapid enough comparing forming fossil fuels.

Thus, the C-sequestration mechanism simply explains the pathways to lockdown carbon into the plants or micro-organism through photosynthesis or in the form of fossil fuels. This process can be taken place though physical, chemical or biological means. And, most importantly the pace of lockdown of C can be accelerated by changing our present agricultural practices and encouraging the agroforestry aspects.

17.4.3 Above Ground C-sequestration

C-sequestration at above ground level is nothing but the measurements involving the summation of standing crop biomass and harvested biomass (Fig. 17.1). Above ground C-sequestration is most important aspect in the agroforestry systems. Under agroforestry system both tree species and crops grown as an intercrop under the forests are very important in C-sequestration. Although majority of the C-sequestration has been done by the tree species as their whole above ground biomass (stems, leaves, inflorescences, etc.), the crops beneath the tree species are

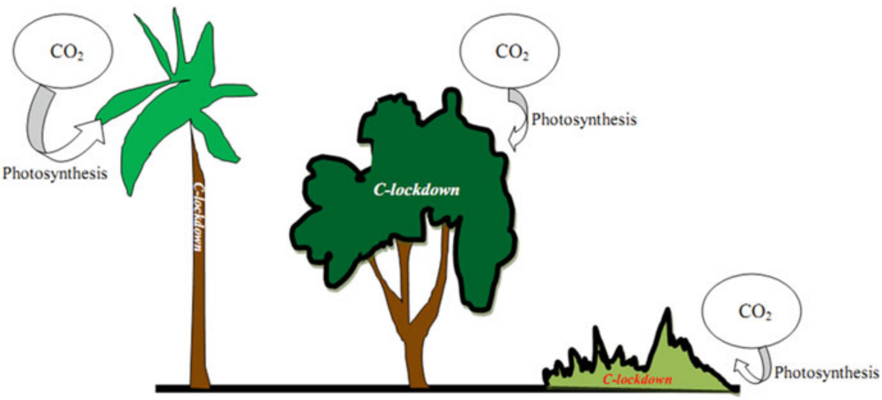

Fig. 17.1 Above ground C-sequestration

also important in this concern. Concerning the C-sequestration by the forest system, it is calculated as per the whole biomass of a tree which is an age old practice. To estimate the whole biomass of coconut, Nair (1979) followed the following steps, such as separating the various parts of a sample tree such as stem, leaves, floral parts; collecting all the roots spread into the soil and then all these parts were dried and biomass of each part was estimated. Afterwards, total biomass was estimated by adding the biomass of separate parts. Then, C contents of each part of the tree were estimated and those were multiplied with the respective biomass to find out the amount of C sequestrated. Estimation of C-sequestration in such a way is obviously a tiresome job. Alternate method using allometric equations was described by Takimoto et al. (2008) to calculate the biomass of standing tree in Sahel. However, a general equation was developed by FAO (1997) which was recommended by UNFCCC (2006) to overcome the problem associated with non-availability of allometric equations for specific tree species. According to Dixon et al. (1993), whole tree biomass was estimated by calculating the biomass of stem which was further multiplied with species-specific wood density. Afterwards, the product of stem biomass and species-specific wood density was again multiplied by 1.6 and thus, the total biomass of a tree was calculated. In general C-content of whole tree biomass was predicted about 50%. This estimation method is globally accepted to calculate the rough biomass of the forest tree and amount C sequestrated by them.

17.4.4 Below Ground C-sequestration

Below ground C-sequestration can be defined as the lockdown of the C beneath the soil by means of soil macro as well as microorganisms, plant roots, hyphal biomass, labile, and non-labile soil organic matter, etc. (Fig. 17.2). However, the method of measuring the below ground C-sequestration is much critical than the estimation of above ground C-sequestration.

17.4.4.1 Measurement and Estimation

Soil organic carbon is primarily measured using the Walkley–Black procedure. In this process, digestion of organic matter of the soil sample was done adding potassium dichromate. The digestion is incomplete, ranging from 60% to 87% depending on the sample (Walkley 1947); therefore, an average correction factor of 1.33 is applied. However, this method is not environment friendly. Currently, soil organic carbon (SOC) measurement is done by measuring the amount of CO_2 produced through heating in a furnace (Nair et al. 2010). Reduction in the weight of the SOC after heating is also other way of measuring the CO_2 produced by the heating of SOC. The results concerning CO_2 production can also be skewed by the presence of carbonate ions as well as charcoal in the soil (Kimble et al. 2001). These methods can give an idea of total CO_2 produced from known amount of SOC. However, concerning the SOC pools in the soil, i.e. labile and non-labile pools, analytical methods are needed to quantify the amount of rapid turnover organic matter to CO_2 and recalcitrant pools. In order to gain a better understanding of these

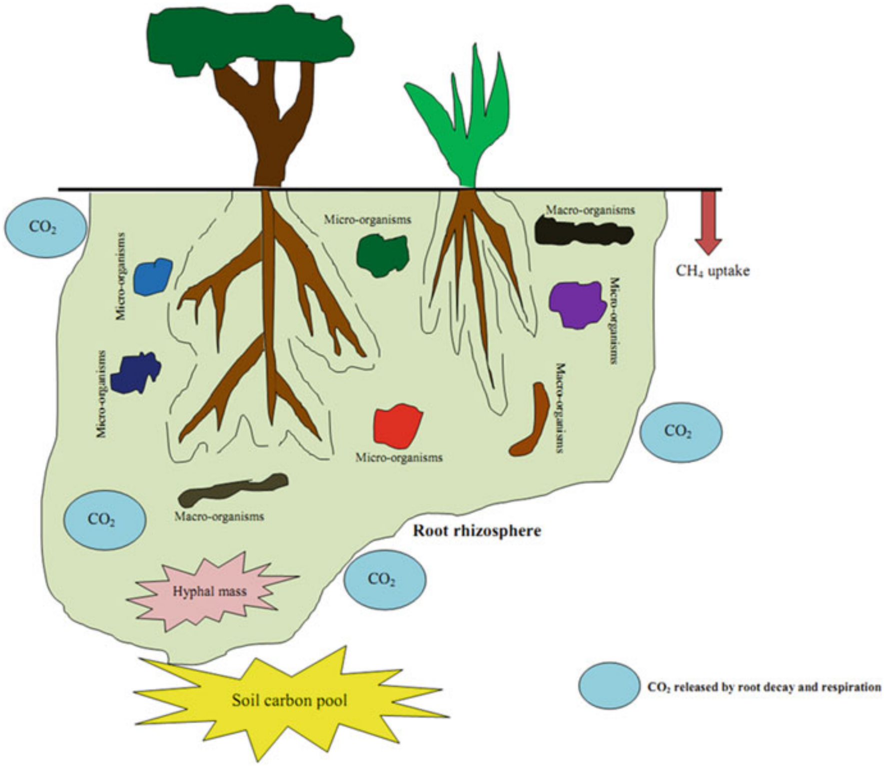

Fig. 17.2 Below ground C-sequestration

details of C-sequestration in soils, attention has focused on the study of soil aggregates.

Soil Aggregates

Soil aggregate measurement is very much important in understanding the below ground C-sequestration. Finding out the amount of micro-aggregate present in the macro-aggregates gives us a complete understanding of the quality of the macro-aggregates and soil organic matter (SOM) as these aggregates are considered as the storehouse of the SOC. Six et al. (2000) developed a method to measure the amount of aggregates formed or presented in the soil. Since the majority of organic carbon in the soil is found in soil aggregates, we can have a better understanding of how carbon is entering, moving through, and leaving the soil by understanding the structure and cycling of these aggregates (Nair et al. 2010). Considering the below ground C-sequestration, most of the studies focuses mainly on SOC build up in soil. However, studies on soil aggregation may give us a complete understanding on the mechanism of C-sequestration; how C enters into below ground rather soil, moves into it and transformation. It also advocates us to find out the factors affecting the aggregate formation which ultimately enable us to select the suitable measurement tactics to improve soil aggregation, thereby, C-sequestration rate can be augmented. Agroforestry system provides a great opportunity to achieve this goal.

Below Ground Living Organisms

Below ground living biomass is very important to improve C pool in the soil (Nadelhoffer and Raich 1992). However, measuring the extent of below ground biomass is not easy at all. Root to shoot ratio is commonly followed to estimate below ground biomass. This ratio varied widely across different ecologies and microbial species. The living microbes are most important for decomposition of the organic matter which releases CO_2, but, for the growth and development of the microbes C is lockdown into their biomass. Common measurements for microbial biomass and activity include chloroform fumigation or adenosine triphosphate (ATP) assays (Vance et al. 1987). Under agroforestry systems, higher activity in the soil microbes observed which is considered as the key to sequestrate more C at below ground level.

17.4.5 Carbon Sequestration Programme and Rural Livelihood Security

Enhancement of C-sequestration programme though agroforestry measures has a great impact on the rural livelihood. Adoption of proper planning to improve C-sequestration though encouraging afforestation, organic culture, cover crops, conservation agriculture, would be beneficial for the environment which ultimately boon for the livelihood security for the rural people. The ultimate aim of C-sequestration programme is to stabilize CO_2 concentration in the atmosphere, so that the adverse effect of global climate change can be mitigated.

17.4.6 Biodiversity Conservation

Biodiversity conservation is a prime concern to preserve the continuity of food chain. It has often considered as the life-support system on the mother earth. Biodiversity conservation is also linked with C-sequestration. It has been observed that C-sequestration potentiality increased with the conservation of biodiversity and vice versa. Society would get the immediate benefits through the biological diversity as well. So, it (biodiversity conservation) provides the entire human community an insurance to live in future. It may be done through two ways, ex situ and in situ conservation.

Ex situ conservation means the natural environment where the biodiversity is conserved in natural way with proper maintenance by the human beings. Botanical park or zoological garden is the live example of it. Another aspect of ex situ conservation is reintroduction of the extinct species of any plant or animal to a place where these species were dominated once. On the other hand, in situ conservation means the conservation of the animals and plants in their natural habitats like reserve forests, national parks, and sanctuaries, etc.

Another important aspect of biodiversity conservation is agro-biodiversity conservation. This is a vital concern in maintaining the biodiversity. Sometimes, the faulty and non-sustainable agricultural practices result in the great loss of the most important indigenous varieties of many crops. Through the concept of agro-biodiversity conservation, this can be stopped. If each and every grower becomes concern about the utility of the conservation of their own seeds, then they must not be dependent on the private sector to buy the seeds they wanted to sell.

17.5 Agronomic Intervention Towards Soil-Centric Approach

17.5.1 Crop Diversification

The monoculture in crop cultivation may be due to easy adoption, ease in resource availability, and policy involved. But continuous adoption of monoculture leads to the deterioration of soil structure, declining organic C and N, underground water, and lower soil and water productivity (Ladha et al. 2003; Singh et al. 2008). For example, the sustainability of the rice–wheat cropping system in Indo-Ganagetic plain is under big threat now-a-days (Kar et al. 2021). This may be due to over exploitation of resources, inadequate nutrients, and inappropriate water management (Singh et al. 2020). Moreover, growing of cereal–cereal crop rotations which have almost equal root growth extraction more amount of nutrients from the same depth and repeated development of anaerobic to aerobic and again to anaerobic growing conditions might affect soil structure, nutrient relations, and crop growth thereby stagnation of productivity rice and wheat (Singh et al. 2020). Crop diversification and intensification are the best option to maintain the soil health. Diversification with the inclusion of vegetables, pulses, maize, and oilseed crops and summer season crop could be able to solve water and labour scarcity and help to sustain the soil health. Inclusion of leguminous crop is comparatively better option to maintain soil health than non-leguminous crops. The critical parameter of crop rotation which affect the SOC sequestration are inclusion catch crops or green manures, having less fallow period, cover cropping, selection of crop, adding legumes/N fixing crops to rotation. The inclusion of mung bean or urd bean in exiting rice–wheat cropping systems enhanced system productivity, available N, aggregate stability, hydraulic conductivity, and biological activities and helped to conserve soil water (Ladha et al. 2003). The inclusion of mung bean in rice–wheat system enhanced the soil organic carbon (SOC), available N, P, K, and micronutrients, soil microbial biomass C and N, and various soil enzymes (Ghosh et al. 2012; Jat et al. 2018). Increasing cropping intensity or reducing the fallow period by including leguminous crops is a suitable option to improve the total biomass production and soil C sequestration. Besides, growing of cover crops improve C sequestration and SOC storage in soil as cropping intensity decreases rate of organic matter decomposition and mineralization/oxidation. Summer cover crops like sunnhemp, velvet bean, sorghum sudan grass etc. are grown during the hot and humid summer to cover the bare land and thus these crops conserve soil and water and reduces the gaseous N loss (Singh et al. 2020). Therefore, cover cropping system provides an excellent strategy to improve C-sequestration for mitigation of climate change.

17.5.2 Water Management

Agricultural activities consumed about 70% of fresh water demand around the globe placed on the top of the utilization of fresh water. Water is an important factor for crop production, as it affects the quantity the total biomass production both inside (roots) and outside (shoots) of the soil. The water deficiency is known to be prime yield limiting factors. It has been reported that crop can produce only 30% of maximum achievable yield due to drought and water deficiency (Fahad et al. 2017). The irrigation, i.e. water application to grow and get maximum yield of crop is an important practices to combat the deficit rainfall and sustain the agriculture production worldwide. Moreover, to meet the increasing demand of agricultural produces and rising concern of water scarcity due to climate change will aggravate the importance of irrigation. However, in the exiting irrigated area the water use efficiency is less than 30% which is major concern for water management. Injudicious use of irrigation water not only leads to its wastage but also loss of water soluble C and N due to increased leaching and runoff. It has been reported that 40% of NO_3–N lost from the root zone when 200 to 300 mm irrigation was applied in silt loam and clay loam soils during dry period (Liu et al. 2020). Irrigation also influences the process of CO_2 mineralization and decomposition and nitrification and denitrification process in soil thereby affect the CO_2 and N_2O emissions. Therefore, precise irrigation application not only enhances the WUE, but also reduces the nutrient loss from soil. An improved water application increased biomass production. Such higher biomass production increases carbon stock into the soil in the form crop residue including roots and dead leaves. But, the injudicious water application increases the duration of anaerobic condition in soil due to higher soil moisture and hence, increases anaerobic soil microbial activities. This anaerobic condition may also increase the decomposition of soil organic matter which leads CO_2 and other nitrogen oxide emission from the soil (Trost et al. 2013). Further, the increased microbial decomposition of soil organic matter lowered SOC content in the soil (Getaneh et al. 2007). The application of water under improved irrigation practices increases the crop dry matter accumulation which also enhances the organic matter in the soil though the incorporation of dried leaves and other parts of the plant into the soil. Experimental results showed that the soil organic carbon were significantly higher in irrigated field than in the non-irrigated cultivated field (Trost et al. 2013). However, the SOC contestant varied with condition like the highest soil organic carbon was found on those fields where natural vegetation exited compared to cultivated field of experimental site. There are many reports where dryland converted to irrigation land there were increased in SOC, however, the percentage increased varied with climatic condition and also interaction with other management factor and in long-term situation (Li et al. 2009). After reviewing the results of different long-term trials, Trost et al. (2013) concluded that conversion of non irrigated desert land into irrigated land resulted in an average increase of SOC about 242.6%. In contrary, application of irrigation showed lower effect on SOC under humid climates. In some cases, soil organic carbon even decreased though it also depends upon the duration of experiments to take SOC data.

The changes in SOC also depend on interaction with other management factors like tillage and fertilizer application. Application of nitrogenous fertilizer increases crop biomass production by increasing root, shoot leaves, and thereby crop residues. Therefore, N fertilization helps to contribute to increase the soil organic carbon content in arable land, however, this also lowered the soil carbon/nitrogen ratio which leads to commence of decomposition of soil organic matter (Li et al. 2009). Nevertheless, the positive relationship has been reported to certain extent in irrigation and N fertilizer. The nitrogenous fertilizer increased SOC compared to without N application at the same level of irrigation and only irrigation with the same level of N did not increased the SOC has been reported by Dersch and Böhm (2001).

17.5.3 Irrigation with Tillage

Reduced or no-tillage increases water productivity of crop than intensive tillage operations as reduced or no-tillage promotes water conservation. Under both reduced and no tillage water holding capacity of soil increases due to preservation of humus and reduction in evaporation. Besides this, in case of reduced or no tillage conditions, the left over crop residues on soil surface act as a mulching materials which can absorb atmospheric moisture. In reduced as well as no-tillage practices, increment in the biomass production per unit of water applied (water use efficiency) was observed (Drastig et al. 2011). Such report depicts the synergistic effect of irrigation and tillage on soil carbon sequestration as higher biomass production increases the SOC as discussed earlier. The irrigation under reduced tillage increased significantly the SOC as compared to irrigation in combination under conventional tillage (Rusu et al. 2008). However, De Bona et al. (2008) reported that the increase in SOC under conventional and no-tillage with or without irrigation was non-significant. Irrigation influenced the stability of soil aggregates, i.e. micro-aggregates (50–250 μm diameter) and macro-aggregates (>250 μm diameter) which bind SOC and provide protection against decomposition. As carbon compound once make matric with soil particle especially silt and clay particles with solid chemical exudates, it is very difficult to dissolve. As the micro-aggregate of agricultural soil is the best indicator for the carbon sequestration since additional carbon inputs are mainly fixed in this (Blanco-Canqiu and Lal 2004). However, some reported the importance of macro-aggregates for SOC sequestration as it is not decomposed after repeated wetting and drying even with intensified microbial activity. The irrigation has influence on soil aggregate binding. The drying and wetting of the soil due to irrigation oprtations has both negative and positive impacts on the of soil-macroaggregates stability. Some previous reports (Mulla et al. 1992) demonstrated the reduction in aggregate stability by breaking the binding matric through alternate wetting and drying, while, some other reports (Barzegar et al. 1995) opined that continuous conversion between wetting and drying increased the water stable aggregates. However, both condition prevailed and depend on soil types and soil composition (Six et al. 2004) and thereby affect the SOC. The soil aggregates also influenced by infiltration rate when moisture enters slowly in soil, there is little effect on soil aggregate stability. On contrary, when water enters rapidly, i.e. high infiltration rate lead to disaggregation of soil particles. However, water saturation of different types of soil may influence the infiltration rate and aggregation of soil (Amézketa 1999). The irrigation intensity also affects the soil organic carbon content by influencing the aggregate stability. It has been observed that quantity of applied irrigation water increased the soil aggregates of diameter over 0.5 mm, while decreased the aggregates of diameter under 0.5 mm and the SOC content increased with higher amounts of applied water (Blanco-Canqui et al. 2010). Apart from rate and duration, the irrigation method may also influence soil aggregates structural stability. The flood or furrow irrigation results in disaggregation of soil aggregates due to rapid soil wetting as well as rapid removal of entrapped air from soil, while, sprinkler and drip irrigation systems have slow and steady infiltration rate which enhance soil aggregate formation at the soil surface. The size of water drops affect aggregates by beating effect on soil surface. The large size with high intensity of water droplets increases the aggregate breakdown on the soil surface compared to small size by its impact force on soil surface. Therefore, precise irrigation with less intensity/flow does not break the soil aggregate and enhance SOC sequestration in soil.

17.5.4 Soil-Centric Approach of Tillage

In conventional tillage (CT) practice, proper tilth of the soil is obtained though the tillage operation by large or small implements for growing a crop. This practice not only required high energy but also causes depletion of SOC by oxidation process. Consequently, release of CO_2 to the atmosphere and thereby by decrease in soil health as well. The best option to maintain soil health is conservation agriculture (CA) which includes conservation tillage either reduced tillage (RT) or no-tillage (NT) with crop residue management, crop intensification with diverse cropping helped in conserving SOC in the root zone. The NT practice creates specific changes in soil physical and biological properties. Less soil aeration in NT practice results in enhancement of soil C stocks as loss of soil C as CO_2 though decomposition is less under such condition. NT practice also impacts on soil N dynamics. As it is well known that soil C and N are interrelated with SOM and complement each other in soil system. Under CA soils can store C because of less soil disturbance, reduction in fallow period, and inclusion of cover crops in the crop rotation. However, SOC sequestration in NT practice is soil/site specific, and the improvement in SOC is inconsistent in fine textured and poorly drained soils. In sub-tropical and tropical conditions, under CT practice SOC decreased more rapidly compared to CA due to prevailing higher temperature in this region (Don and Schumacher 2011). Under NT practice SOC stabilizing in micro-aggregates and protected from easily decomposition. Consequently, this SOC in soil micro-aggregates contributes to long-term soil C-sequestration in soils. NT with residue retention on soil surface has shown significant increase in SOC pool in the top 0–30 cm layer after 43 years of continuous corn crop (Ussiri and Lal 2009).

17.5.5 Soil-Centric Plant Breeding Approaches

17.5.5.1 Breeding for Enhancing Nutrient Use Efficiency

Breeding approach has proven its worth by securing the food to sustain the world population. The increasing productivity of crop is the prime objective of breeding programme. The high yielding varieties either composite of hybrid perform better when supplied with high/optimum level of nutrients/fertilizers and water. Consequently, the world agriculture produced more per unit of land means extract much nutrient without supplying the balance nutrient to the soil thereby the crop. The use of fertilizers especially inorganic fertilizer (N, P, K) in agriculture has substantially around the globe. The inorganic fertilizer application is a simple practice of crop management to get maximum yield by providing readily available nutrients to crops to plant growth and development and thereby. But from an ecological aspect, easily manageable crop management practice creates imbalance of nutrients in the soil ecosystems which affects soil carbon dynamics. Many studies have been reported that enduring nitrogen additions to soils systems decrease soil microbial activity (Frey et al. 2014) and thereby the soil health. Deterioration of soil health has been reported around the globe and in India too, due to practice of monoculture and injudicious use of fertilizers, pesticide and water. The green revolution which brought food security in this region but it is compromised with soil health. In the future, maintaining high input systems will become increasingly difficult due to reductions in the availability of required resources, such as water and nutrients. Again the breeding approaches will have to play important role in sustaining the agricultural production. The soil centric breeding approaches aim at development of varieties which are of high nutrient, water and energy use efficient. By breeding approaches development of improved nitrogen use efficient cultivar will be possible. These cultivars will provide higher yield with reduced fertilizer consumption making the crop nutrient as well as energy efficient. Baligar et al. (2001) estimated applied nitrogen fertilizers efficiency is around 50%, and that can be enhanced by improvements in uptake and utilization of nitrogen in plant system. Several studies have shown that crops produced under high- and low-N inputs had several traits, genetic inheritance (Bertin and Gallais 2000), indicated that there are different genetic elements and those responded differently with different inputs. As almost all crops have been bred since long under high input production system, a perfect understanding of mechanisms involves an inheritance of NUE is lacking under low-input systems. Many adaptation mechanisms such as delayed leaf senescence, improved root development, increased root microbial association, nitrogen fixing symbioses, increased activity of specific enzymes etc. have been reported for enhancing the nutrient use efficiency (NUE) of the crop but none of them are fully recognized for NUE as it is a complex phenomena (Vance 2001). However, improvements in root structure such as increasing length, thickness, density and by increasing the production of root hairs and adventitious roots are efficient ways to improve the ability to absorb soil nutrients thereby NUE. Such improvement in root architecture also enhances phosphorus use efficiency. Many research works were conducted to increase phosphorus uptake efficiency by improving the morphology or physiology of the root system. But, organic acid production and exudation from roots which establish strong mycorrhizal associations lead to more efficient phosphate uptake systems. Moreover, better understanding of phosphate physiology, which include less allocation of phosphate towards phytate biosynthesis and accumulation need to be developed. The total amount of phosphorus may be high in many soils. However, it is mostly presented in organic forms that are unavailable to the crops. Therefore, it is needed to breed crops which can be more phosphorus use efficient through altering root structure, allocating more carbon to the roots, and increasing the root-to-shoot ratio (Williamson et al. 2001). This not only enhances the P use efficiency of plant but also left large quantity of root in soil which will improve the soil health in long run after decomposition. The breeding for increased root depth and distribution would also be helpful to grow the crop under dry condition as deep root access to water reserves in deep soil (Richards 2000).

17.5.5.2 How Does the Deep Root Help in Carbon Sequestration?

The rhizosphere is the interface between plants root and soil that plays crucial role in carbon sequestration as exudates/organic chemical secreted from roots by mycorrhiza that form symbiosis relationship with plants (Zhu et al. 2003; Leigh et al. 2011). The mycorrhizal fungi help to mobilize the soil nutrients and make them available to plant, especially phosphate, and also they provide up to 20% of the carbon to the soil dwelling fungus. Though the symbiosis relationship have been observed among roots, mycorrhiza and soil organic carbon (SOC), but, the interactions are too complex to understand (Kariman et al. 2018). The porosity of soil increases when more soil biota and roots hair present and that root affects the physical properties of soil and vice versa (Hinsinger et al. 2005). Mycorrhiza known to secrete a protein called glomalin, which bind the aggregated and make desirable large aggregates in soil structure and thereby by benefits to carbon sequestration in soil (Pal and Pandey 2014; Wilson et al. 2009). The root density reported to improve soil structure, hydrology, and SOC which ultimately improves agronomic productivity (Lal 2010). There are many crops which have strong root systems and high root biomass does contribute significantly to SOC sequestration.

17.6 Forest-Crop Interaction Towards Soil-Centric Approaches

Agricultural sustainability, food production, and the livelihoods of farmers are at stake owing to the variability of the current climate, changes in the mean temperature values and their future projections (Izumi et al. 2013). The productivity of most of the crops is sensitive to extreme occurrence of temperature and precipitation such as drought or flood stress (Gregory and Ingram 2000). Agricultural vulnerability to varying temperature and precipitation patterns points to the need to develop climate-resilient systems that can buffer crops from climatic inconsistency and extreme climatic events, particularly during crucial developmental periods. Various climatic variation studies also pointed out the urgent need to develop adaptive agroecosystems because most of the rural farmers depend on rainfed and subsistence agriculture for their livelihood needs (Haile 2005; Verdin et al. 2005). Agro-ecosystem is emerging as one of the best tools for climate-resilient agriculture, which is the system of integration of forest trees and crops together. Sometimes fodder crops, pastures, animals, etc. are also integrated with forest trees in agroforestry.

17.6.1 The Utility of Agroforestry Under Future Climate Change Scenarios

There are many methods of agricultural mitigation against climate change are available and wide ranging, depending on the level of climate stress and the scale of the operation. Some adaptation strategies include the variability in crop varieties, species or planting times, and simple changes to management that provide more water to plants, on the first level. As climatic risks increase, the adaptation strategies should lead to greater changes in agroecosystems using technological approaches such as precision agriculture, agricultural diversification, and risk management approaches for the agricultural business system. At the higher extreme level than above, farmers must adopt more extreme measures that may include a change in the landscape distribution and use or even sell of ecosystem services as an income stream for the land. With the anticipated increase in climatic fluctuations and more extreme variation, the range of adaptation option's available decreases, while the cost and complexity of implementing the options increase. The need to implement adaptation and the benefits of adaptation also increase as climate variability increases (Howden et al. 2010).

Agroforestry combines the production of livestock or food crops with growing trees for timber, firewood, or other products (Montagnini and Nair 2004). Some of these systems, particularly the traditional ones, provide high species diversity within a small area of land (Leakey 1999; Kumar and Nair 2006). They provide a great range of diversity of crops in time and space, at the same time they also protect soil from erosion and provide litter for organic material and soil nutrients (Jama et al. 2000) and in this way reducing the need for synthetic fertilizer. Agroforestry is a specific type of agriculture that allows a high level of progressive adaptation from changing crop varieties to selling ecosystem services for increased economic diversification. The ability of agroforestry systems to provide a buffer for crops and farmers to adapt to changing climate parameters enhance the utility of this type of specific agriculture system in maintaining production levels under potentially difficult future scenarios.

By considering the assemblages of multiple species, as created by agroforestry, overall biodiversity is increased, and ecosystem services are optimized. It is recognized that agroforestry, and other diversification processes such as intercropping, show greater similarities to natural ecological systems than intensive modern agricultural practices such as monocropping. In such systems that mimic nature, better use may be made of resources including sunlight, soil nutrients, and rainfall (Ewel 1986; Vandermeer 1995). In general, increasing tree density in the landscape creates a buffer to reduce the impact of floods and droughts on farming systems. The ability of increased complexity in agroforestry systems (associated with the roots, trunks, and capture of organic matter by trees) reduces surface water runoff and increases infiltration and soil water-holding capacity. These processes reduce the risk of flash floods during heavy rainfall and storms (Smith 2012).

Trees in the particular landscape are also beneficial in providing the important service of dropping damaging wind speeds of extreme storm events to protect crop production. Windbreaks grown perpendicular to prevailing winds can increase farm production by merely reducing wind and modifying the microclimate. In citrus and vegetable systems, windbreaks reduced wind speed by up to 31 times the windbreak height on their leeward side. However, there was significant inconsistency in this reduction depending on the height and porosity of the windbreak and wind direction relative to the windbreak (Tamang et al. 2010). Higher air and soil temperatures on the leeward side of shelterbelts can also extend the growing season by allowing earlier germination and more rapid initial growth (Brandle et al. 2004).

Agroforestry systems offer additional income from both timber and non-timber products provided by shade trees (Somarriba et al. 2004). Agroforestry may also benefit farmers by mitigating agricultural production of greenhouse gases from the production system. There are several pathways by which this may be achieved, including increases in carbon capture in agroforestry systems to levels exceeding conventional agricultural systems and preventing unnecessary emissions of greenhouse gases from the specific management techniques used.

The use of trees within these agricultural systems affects temperature, soil factors, light, disease, and pests, as well as the quantity and composition of biomass (MacLean et al. 2003). It will have ramifications for their future productivity under climate change.

17.6.2 Mitigating Temperature Change

Agroforestry systems have the potential to mitigate temperature variations. The application of mulch may reduce soil surface temperature, which in turn affects the spread of pests and diseases and may help to suppress weeds. As soil temperature is often the main determinant of survival of insect larvae in many tropical areas (Riiser and Hansen 2014), management practices such as pruning and mulching can create unfavourable environments for pest establishment.

17.6.3 Maintaining Soil Water

Considerations of both below and above ground competition are critical in assessing the suitability of a system. For example, alley cropping using *Leucaena leucocephala* showed much greater below ground competition than the above ground competition (Monteith et al. 1991). The age and the size of trees also influence the degree of competition (Hocking and Islam 1997; Umrani and Jain 2010). This suppression effect can be so profound that, within 5 years, underground competition can limit crop production by 80% in a *Leucaena*–millet alley system (Umrani and Jain 2010). However, due to the contrasting rooting depths of crop components and trees (Bhatt and Misra 2003; MacLean et al. 2003), competition for light is often of greater importance in limiting productivity (Umrani and Jain 2010).

17.6.4 Maintaining or Improving Soil Quality

Smallholder and marginal crop farmers face a number of problems that can be addressed through the adoption of agroforestry, one of which is depletion of soil quality and structure due to the lack of inorganic fertilizers. The phenomenon of improved soil fertility in agricultural systems following tree introduction is already well documented and led to the adoption of the concept of “islands of fertility” (Pinho et al. 2012).

17.6.4.1 Soil Carbon

Soil organic matter consists of animal, plant, and microbial residues and provides a reservoir of nutrients for plant growth and development. As Rutherford et al. (1992) concluded that approximately 58% of soil organic matter is carbon, soil carbon is often used as an indicator of the soil organic matter content for specific soils. The ability of a soil to accumulate carbon, and thus organic matter, is greatly influenced by management practices such agroforestry, suggesting that the introduction of trees could increase carbon content, especially closer to tree trunks and that the stable carbon content will increase with tree age (Gupta et al. 2009; Baah-Acheamfour et al. 2014). The choice of tree species is essential in determining the extent of the effects of agroforestry. For example, Das et al. (2010) showed that incorporation of the leguminous species, Erythrina indica, increased soil carbon by up to 14%. However, the average carbon increase reported in the literature is 5% (Riiser and Hansen 2014).

17.6.4.2 Soil Nitrogen

Soil pH and nitrogen are two such examples and are properties that may be exploited using appropriate management practices (Pinho et al. 2012). Both nitrogen-fixing and non-nitrogen-fixing trees can improve soil fertility, although the degree of improvement depends on the species chosen. Species that do not fix nitrogen may still contribute by retrieving nutrients from deeper soil horizons or through the decomposition of litter or pruning on the surface of the soil (Umrani and Jain 2010).

17.6.4.3 Soil Phosphorus

Depletion of soil phosphorus is often difficult to reverse, although the application of agroforestry contributes three key properties to manage and protect the existing phosphorus reserves. Tree cover reduces erosion and decreases runoff. The ground cover provided by trees helps to retain the phosphorus in the system within plant matter. Deep-rooted species are able to retrieve phosphorus from deeper soil horizons and make this available to associated annual crops following litter fall or the application of mulch.

The potential of agroforestry lies in situations where land availability for agriculture is limiting or in allowing barren or deteriorating soils to be used for agricultural production. Agroforestry systems in which crops are grown under scattered trees are the most simple and popular systems among smallholder farmers (Nair 1993). The mitigation strategy to climate change offered by agroforestry systems may be highly efficient on several fronts. Its capacity to mitigate the effects of growing temperature variability, variation in rainfall quantity, and intensity and wind and storm occurrences has been shown to protect agricultural production under more extreme climatic situations. The prospective of agroforestry systems to sequester carbon within plant biomass and soil stocks, combined with the ability to decrease the amount of greenhouse gas emissions using appropriate management and resource cycling techniques, is also beneficial in reducing the contributions of agriculture to climate change.

17.7 Conclusion

In this chapter, efforts were made to highlight the importance of soil-centric approaches enlightening the rights of soil as all other living organisms. As SOC is one of the most important factors to determine the soil quality as well as success of agriculture, the maintenance of the optimum level of SOC must be there. Presently the SOC level of the soils is depleting in an alarming rate. And this situation can be rectified through the adoption of the soil-centric approaches in agriculture. The SOC levels of the tropical and subtropical soils are reducing at an alaming rate. This is mainly because of unscientific management of the soil which must be rectified with proper soil centric interventions to sustain the health of the soil so that the agriculture can be sustainable.

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Functional Diversity Management through Microbial Integrity for Sustainability

18

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Abstract

Soil biodiversity is essential for many soil processes/functions and it is facing increasing pressure of soil degradation. Soils are integral part in tackling challenge of present-day agriculture in achieving food security to expected population in the coming decades. Tackling issues of productivity stagnancy, biodiversity loss, and extreme weather changes associated with climatic variability should go in hand with ecological conservation aspects. Soil has a component with potential to collectively address the issues of yield decline, functionality loss, and climate variabilities. This component is soil biota which makes the soil healthy with functional biodiversity and supports unhindered crop growth by buffering extreme conditions. By establishing or restoring functional diversity of soil, soil health and respective benefits can be assured. Eco-friendly and optimized resource management practices will help in increasing functional diversity and thus help in promoting microbial integrity of soil and bringing accompanying advantages to crops in terms of sustained yield, stress tolerance, and climate resilience. Carbon sequestration, organic matter decomposition, nutrients transformations (mineralization, immobilization, nutrient cycling), soil bioturbation, biological nitrogen fixation, plant growth promotion, growth hormones/vitamins synthesis in root zone, moisture stress alleviation, bioremediation, and biocontrol are some of the many functions ascribed to rhizospheric and general soil biological communities (multiple ecosystem services/multifunctionality of soil biota). However, all these functions get disturbed due to agricultural intensification in terms of heavy tillage, high fertilizer/pesticide application, residue burning, monoculturing, and many other operations. Soil biodiversity loss and

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reduction of soil community composition impair above listed ecosystem multifunctionality and threaten sustainability. Recent research studies backed up by both traditional methods and molecular biological tools (next generation sequencing and genomic tools) are establishing the linkage between ecosystem biodiversity with its ecosystem function which is a substantial scientific challenge. It is now being understood that high degree of diversity in functional groups will increase the inherent variability in tolerance or resistance to stress or disturbance. If biodiversity is reduced and organisms become extinct, the associated soil functions will also be lost. However, restoration or enhancement of biodiversity will lead to the restoration of functions and of resilience. Thus, by understanding redundancy in performing same function by different species or genus in soil, one can reduce the impact of loss of that particular species or genus by encouraging establishment of species or genus with same function. Such development of microbial function integrity will act as buffering against intense management practices or climatic variations and help in securing sustained crop yield. Promoting functional integrity of microbes through approaches aimed at enhancing diversity will contribute immensely to agricultural sustainability.

Keywords

Microbial integrity · Ecosystem services · Functional biodiversity · Soil health · Microbial community composition · Multifunctionality · Land-use intensification · Ecological intensification

18.1 Introduction

Sustainability is observed when the system can maintain its structure (organization) and function (vigor) over time in the face of external stress (resilience). The structure (organization) and the ecological function of soil depend on a healthy and dynamic community of soil biota. In this respect, soil and its biotic component have been described as “our most precious non-renewable resource” (because soil cannot be replenished within a human lifespan). To promote and maintain soil health, we need a fundamental shift in the way we view soil—from a medium that supports human activities to a dynamic, multifunctional ecological component of the larger biophysical and socioeconomic environment. An ecosystem health approach to evaluate and manage of soil health, with focus on interrelationships among ecosystem components, integrated multisectoral management, and the role of culture, values, and socio-economic systems is contemporary research interest of soil biology. Ecosystem integrity and ecosystem health are two ecological concepts that have emerged as part of this ecosystem approach. Ecosystem integrity comprises the functional and structural attributes of an ecosystem in terms of resilience, biodiversity, and freedom from human impact. Ecosystem health is used in a broader sense as a transdisciplinary science integrating together ecology, geography, ethics, environmental management, and health sciences (Rozzi et al. 2015). Soil biota and biodiversity are synonyms which describe the array of interacting, genetically distinct populations and species in a region, the communities they comprise, and the variety of ecosystems of which they are functioning parts. Biodiversity is not always a synonym of ecological quality but only when applied to the species belonging to a particular ecosystem (Ahlberg 2013). The concept of stability—including the aspects of constancy, persistence, and resilience—relates to the differential response of the communities to disturbances. Insights into the mechanisms maintaining biodiversity are mandatory for guiding the development of management practices that will prevent future biotic degradation (Alkorta et al. 2003; Bellard et al. 2012).

Challenge of present-day agriculture is achieving food security to expected population in the coming decades while tackling issues of productivity stagnancy, biodiversity loss, and erratic weather changes associated with climatic variability. Hence research in agriculture is reinventing towards overcoming aforementioned issues. For sustaining and enhancing crop productivity the focus is now on optimizing resources and management strategies to achieve full yield potential of existing cultivars rather than over depending on breeding new ones. Similarly, to address issue of biodiversity loss together with agro-ecological functions linked with the lost diversity, the ecosystem services of component communities are being studied under different ecological and management situations. Thirdly, climate is also bringing stressful conditions on crop growth like drought, waterlogging, heat, cold, frost, and salinity all of which cumulatively restrict crop yield potential to half the capacity and cause additional yield losses up to 50%. In this background, one promising ray of hope which has potential to collectively address all the issues of yield decline, diversity loss, and climate variability is healthy soil with functional biodiversity that supports unhindered crop growth by buffering extreme conditions. By restoring or establishing functional diversity of soil, sound soil health and respective benefits can be assured. Eco-friendly and optimized resource management practices will help in promoting microbial integrity and thus help in increasing functional diversity of soil thus bringing accompanying advantage to crops in terms of sustained yield, stress tolerance, and climate resilience. Carbon sequestration, organic matter decomposition, nutrients transformations (mineralization, immobilization, nutrient cycling), soil bioturbation, biological nitrogen fixation, plant growth promotion, growth hormones/vitamins synthesis in root zone, moisture stress alleviation, bioremediation, and biocontrol are some of the many functions ascribed to rhizospheric and general soil biological communities (Whipps 2001). However, all these functions get disturbed due to agricultural intensification in terms of heavy tillage, high fertilizer/pesticide application, residue burning, monoculturing, and many other operations. Extensive research in recent time is shedding light and establishing the linkage between ecosystem function and ecosystem biodiversity which is a substantial scientific challenge. Soil biodiversity loss and reduction of soil community composition impair above listed ecosystem multifunctionality and threaten sustainability. High degree of diversity in functional groups will increase the inherent variability in tolerance or resistance to stress or disturbance (Laureto et al. 2015). If soil functions are lost as biodiversity is reduced and organisms become extinct, then restoration or enhancement of biodiversity will lead to the restoration of functions, and of resilience (EU Biodiversity Strategy for

2030 document 2020). Thus, by understanding redundancy in performing same function by different species or genus in soil one can reduce the impact of loss of that particular species or genus by encouraging establishment of species or genus with same function (Jurburg and Salles 2015). Such development of microbial function integrity will act as buffering against intense management practices or climatic variations and help in securing sustained crop yield (Miguel et al. 2015). Plant diversity also influences soil microbial communities, and this is a two way relation as monocots and dicots preferentially help in establishment of selective communities and vice versa (Schmid et al. 2020). Similarly, some plant types show declined productivity on depletion of soil biodiversity (e.g., legumes), whereas few show increased productivity under most simplified soil communities (e.g., grasses). Accordingly promoting functional integrity of microbes through approaches aimed at enhancing diversity will contribute immensely to agricultural sustainability (Maron et al. 2018). Some of the aspects of microbial integrity and their mechanisms are discussed in this chapter. The ways to understand contributions of microbial ecological services to improve overall functional diversity of soil are also briefly discussed.

18.2 Soil Biodiversity

Biodiversity is defined as the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems (Convention on Biological Diversity). Soils are home to more than 25% of the earth's total biodiversity and soil biodiversity refers to all organisms living in the soil. Soil organisms are major components of all soils. Soils are among the most biologically diverse habitats on earth and contain the most diverse assemblages of living organisms. A typical gram of soil contains 1 billion (10^9) bacteria comprising tens of thousands of taxa and up to 200 m fungal hyphae possibly with 4000 different microbial genomes apart from a wide range of nematodes, earthworms, and arthropods. As a comparison, the entire bacterial diversity of these may be unlikely to exceed 2×10^6, whereas a ton of soil could contain 4×10^6 different taxa, indicating extremely high diversity in soil (Bender et al. 2016).Typically, $<1\%$ of the total bacteria are recovered by classical cultivation techniques from most soils (Ingham 2000). But this cultivation approach has the advantage that the isolated organisms are available for further study. Due to limitations of traditional cultivation-based methods, molecular approaches based on the examination of extracted nucleic acids are becoming more and more useful in soil microbial ecology. Biological activity in soils is largely concentrated in the topsoil. The biological components occupy a tiny fraction ($<0.5\%$) of the total soil volume and their biomass is low compared with the mineral or humus fraction (Ferrari et al. 2005). Even though the living fraction makes $<10\%$ of the total soil organic matter, its activity is absolutely crucial for a functioning soil. The soil biota can be regarded as the "biological engine of the earth" and is implicated in most of the key functions soil provides in terms of ecosystem services, by driving many fundamental nutrient cycling processes, soil structural dynamics, degradation of pollutants, and regulation of plant communities (Breure 2004). Microbially driven soil processes play key roles in mediating global climate change, by acting as C sources and sinks and by generation of greenhouse gases such as nitrogen oxides and methane.

Soil organisms are normally classified based on their body width (size class) whose variation within soil communities spans several orders of magnitude. Soil biodiversity is composed of microbiota (such as bacteria, archaea, and fungi that forms bulk of soil diversity), micro, meso, macro, and even megafauna (e.g., mammals, reptiles). Soil biodiversity also encompasses huge variety of photosynthetic organisms such as lichens and plants (roots) with key roles in soil ecosystem structure. In terms of activities, soil microbiota contributes mainly to decomposition processes, carbon and nutrient cycling, plant growth regulation, and disease suppression. These organisms also play important symbiotic interactions with plants, improve nutrient uptake, and/or regulate plant hormones. Soil microfauna includes organisms of around 100 μm diameter (e.g., nematodes, protozoa, and rotifers). They feed on bacteria, fungi, and algae, but they also present predator and saprophytic groups. By their activities they regulate nutrient cycling by improving the availability of nutrients to other species (e.g., through their feces), population size and activity of bacteria and fungi, and dispersion of crucial rhizosphere microbiota. Their deleterious effects to plants are also known, when microfauna inhabits in more direct contact with roots, by feeding on those roots or changing plants defences or hormones. In soil mesofauna (organisms of around 100 μm to 2 mm diameter size), main groups are Acari, Collembola, Tardigrada, Protura, Diplura, and Enchytraeidae. These organisms are mainly herbivores, bacterivores, or fungivores. In some cases, they also feed on other soil organisms belonging to higher trophic levels. They live in close contact with the air and water present in soil and therefore are very dependent on soil aeration and moisture. These organisms contribute to nutrient cycling, pest and disease suppression, serve as food for other soil organisms, and participate in soil biota distribution. Soil macrofauna are organisms of around 2 mm diameter that comprised of macroarthropods (e.g., isopods. Spiders, insects) along with soft-bodied organisms (e.g., annelids, gastropods). This group is the mainly responsible for litter fractionation and predation on other soil-dwelling organisms, often called ecosystem engineers as these organisms are responsible for changing the habitat structure, in terms of its physical, chemical, and structural properties, contributing to different soil functions such as decomposition and nutrient cycling, water infiltration (e.g., by burrowing behaviors), suppression of pests and diseases, and as predators regulating other biota (Brussaard et al. 1997).

18.3 Levels of Microbial Diversity

The biological diversity is categorized into three different levels—species diversity, genetic diversity, and community/ecosystem diversity which applies to microbial diversity as well.

18.3.1 Species Diversity

Species are a group of similar organisms that share a common lineage, interbreed, and produce offspring and called as basic unit of classification. Species diversity is commonly used as a synonym for "biodiversity." The species diversity has evolved attributing to the diversity in habitat of living organisms and defined as variety of species within a habitat. Thus, based on the number of species within an area the diversity of that region can be measured. In any area of study, the species diversity is comprised of the total number of plant and animal species in that area. Although some regions have fewer species than others, diversity is present. For example, agricultural ecosystem has fewer varieties in species than the undisturbed natural system such as tropical forests showing higher richness of species but both types of ecosystems agricultural and natural have diversity. Species diversity is studied at different levels: alpha, beta, gamma, delta, and omega species diversity. The diversity within a particular area or ecosystem, usually expressed by the number of species (i.e., species richness) in that ecosystem is the measure of alpha diversity (α-diversity). A comparison of diversity between ecosystems, usually measured as the amount of species change between the ecosystems is beta diversity (β-diversity). Evaluation of species diversity on comparative scale to find unique species in both/many ecosystem (pair wise in case of many ecosystem) gives β-diversity. A measure of the overall diversity within a large ecological region is gamma diversity (-γ-diversity) and it is geographic-scale species diversity. Even further, the diversity in species of biomes and biosphere are measured as delta and omega diversity, respectively. Biomes also referred to as ecosystem are geographically and climatically defined regions.

18.3.2 Genetic Diversity

Genetic level of diversity is defined on variable genetic characters for genetic makeup of a species. Every single organism obtains special characteristics encoded by the broad range of possible combinations in the genes. Genetic variation shapes and defines divergence among individuals, populations, subspecies, species, and strains ultimately at the kingdoms of life on earth. Large number of strains and varieties within a species are considered as diverse and rich in genetic organization. Chromosomal or gene mutations cause the genetic variations in single individuals of a species. Existence of variability in genetics of individuals of a population is important which results in diversity and enables certain population of microorganisms to adapt to extreme environment. These genetic variations are an important aspect and an integral part of biodiversity and considered as prerequisite for adaptation and evolution. Genetic variations are studied at population level and expressed in terms of alleles. PCR (polymerase chain reaction), DNA fingerprinting, allozyme analysis, DNA sequencing, and restriction site mapping are the currently employed different techniques used to measure the genetic variations. Woese et al. (1990) using phylogenies based on ribosomal RNA sequence proposed classification system of organisms in three domains, as bacteria, archaea, and eukarya. This classification is based on divergence in genetic material of most conserved sequences of 16S rRNA gene in the bacteria and 23S rRNA gene in other two domains, i.e., archaea and eukarya. Genetic diversity is much higher in domain Bacteria and Archaea than that of the domain Eukarya.

18.3.3 Community Diversity

Variety of different ecosystems, based on the differences in the habitat, have their own complement of distinctive interlinked species. Distinctive natural ecosystems include aquatic ecosystems like the sea, lakes, and rivers and as well as landscapes like mountains forests, deserts, grasslands, etc. Different landforms may exist in ecosystem, each of which supports specific and different vegetation. By supporting selective communities, agricultural landforms form a kind of ecosystem which is referred to as agro-ecosystems. Agricultural or natural ecosystems become degraded and less productive when misused or overused. Ecological diversity is defined as the variety and abundance of species in different habitats and communities in the ecosystem level and even higher levels (biome and biosphere). In any large ecosystem, several sub-ecosystems are constituted that are separated by the boundaries of the communities that are not distinct and thus, the ecosystem diversity is difficult to measure in comparison to species and genetic diversity. Hence, within the given ecosystem, communities are studied in various ecological niches to measure the ecosystem diversity. The diversity of ecological units or community types within different and large ecological niches is called as community diversity. Thus ecosystem diversity is often used as synonym to community diversity. The loss of species and associated genetic diversity ultimately results in loss of ecosystem diversity. The ecosystems with various functional traits (functional diversity) provide high productivity, resistance, and resilience to invaders and are better operated. The extent of functional differences within the species pool should be studied to better understand the functional diversity. In ecological systems, different organisms perform a range of functions summarized as functional diversity. Within the community or habitat, the species can be divided into functionally similar taxonomic entities like deposit feeders, suspension feeders, etc. or into distinct functional types like plant growth forms, feeding guilds. These functionally similar species within the habitat can be from different taxonomic entities (Sehgal et al. 2019).

18.4 Functional Diversity

Soil organisms can be classified also according to their functionality, which helps to elucidate about their ecological roles within soil ecosystems. Functional diversity (FD) is defined as a set of functional traits in a given community (Table 18.1). Functional diversity describes the biological role of species or groups of species in an ecosystem. It is a description of the different ecological processes, performed by

Table 18.1 Biological functions/ecosystem services, responsible soil biota and management practices most likely to affect them

Soil domain	Biological functions	Functional groups	Influencing management practices
Physical	Soil particles aggregation, porosity, water movement, bioturbation (mixing), organic matter shredding (comminution), organic matter redistribution, microbial conditioning of organic residue (detoxification of allelochemicals, softening)	Roots, fungal hyphae, bacteria and earthworms, meso/macrofauna, (ants, termites, nematodes, earthworms), molluscs, insect larvae, mites, isopods, diplopods, annelids, basidiomycetes fungi	Burning, soil tillage, pesticide applications
Chemical	Elemental transformation, immobilization, mineralization, organic matter decomposition, carbon capturing (carbon sequestration)	Nitrifier bacteria, denitrifier bacteria, dissimilatory nitrate to ammonia reducer bacteria, sulfur oxidizer bacteria, sulfate reducer bacteria, iron oxidizers, iron reducers, Mn, Zn-transformers, AMF, decomposing bacteria, saprophytic fungi, microbial biomass (fungal biomass as carbon sink), earthworms, microfauna, plant roots	Fertilization, soil tillage, burning, reduction in crop diversity, irrigation, pesticide applications
Biological	Nitrogen fixation, element cycling, mineralization, immobilization, carbon fixation (autotrophs), soil respiration, methane production and consumption, hydrogen oxidation, hydrogen production, butyrate oxidation, propionate oxidation, denitrification, nitrification; population control (competitive relationships) like predators/grazers, parasites, pathogens; microbial loop systems; mediation of transport of essential elements and	Free and symbiotic nitrogen-fixers, fungi and bacteria, AMF, nematodes, insects, collembola, protozoa, soil viruses, waste decomposing fungi and bacteria, cyanobacteria, photosynthetic bacteria	Fertilization, reduction in crop diversity (monoculture), soil tillage, irrigation, burning, pesticide application, mining, chemical degradation

(continued)

Table 18.1 (continued)

Soil domain	Biological functions	Functional groups	Influencing management practices
	water from soil to plants, mediation of plant to plant transport of essential elements and carbohydrates, plant essential elements chelation, regulation of photosynthetic rate of plants; biofilm production, mycorrhizal association helpers; plant growth promotion; humus synthesis (humification); biocontrol (plant pest and disease suppression); restoration and purification of soil and water		

single organisms, populations, and communities. For example, "nitrogen fixation from the air" is a function performed by group of eubacteria called diazotrophs. In terms of diversity, this group is represented by symbiotic N-fixers, free living N-fixers, and photosynthetic N-fixers (cyanobacteria). Also, functional diversity of nitrogen fixing organisms not only includes species diversity and abundance, but also in the actual and maximal capacity of the ecosystem performing that function. Functional diversity is the diversity of species trait in an ecosystem as multifunctionality is another aspect of functional diversity. For example, photosynthetic N-fixers (cyanobacteria) simultaneously fix atmospheric nitrogen and carbon along with release of oxygen. Hence, degree of functionality of different genera is also studied under the term of functional diversity. Functional diversity influences ecosystem dynamics, stability, productivity, nutrient balance, and other aspects of ecosystem functioning. Functional diversity measures the performance of a given function by microbial communities and their distribution in given ecosystem. It tries to address aspects of impacts of activities performed by microbes on that particular ecosystem. For example, impact of photosynthetic organisms in freshwater ecosystem (small lake) is measured in terms of biomass production, life supporting activity through oxygen production, and food generation for other trophic levels like fish, etc. Functional diversity also considers the complementarity and redundancy of co-occurring species. Functional diversity is usually predicted for its ecosystem productivity and vulnerability through its member's diversity.

In recent years, functional diversity of rhizosphere has become important topic of research by its influence on crop production and plant health. The rhizosphere is a narrow zone of soil immediately surrounding to the plant roots and is the zone of high biological activity in terms of nutrient cycling, symbiotic/non-symbiotic interactions, and plant growth promoting activity. Plant growth promoting rhizobacteria (PGPR) enhance plant growth by a wide variety of mechanisms like biological nitrogen fixation, phytohormone production (IAA), phosphate solubilization, siderophore production, 1-aminocyclopropane-1-carboxylatedeaminase production (ACC), exhibiting antifungal activity, production of volatile organic compounds (VOCs) promoting beneficial plant-microbe symbiosis, interference with pathogen toxin production, etc. The functionality of PGPR in agriculture is bit by bit increased with its diversity. PGPR are more diverse within two broad categories in accordance with their mode of association with the plant root cells: extracellular PGPR (ePGPR) and intracellular PGPR (iPGPR). These two classes only differ on the basis of their ecological niche, even as the habitat is same for both, i.e., rhizosphere. The functionally diverse groups of rhizosphere include fluorescent pseudomonads, bacillus strains, actinorhizal bacteria, endospore forming bacteria which work simultaneously (complementing each other) or individually to produce plant growth enhancing effects.

With more than 75% of soil organic carbon residing in the top meter of soils, soil management plays a key role in how soils may act as a sink and store more C. Belowground C is stored as organic matter, it represents a dynamic pool that can be diminished through respiration, emitting greenhouse gases like CO_2, methane (CH_4), and nitrous oxide (N_2O), or enhanced through organic matter inputs, namely roots, detritus, and soil microbial biomass. Through these processes, soil is a critical part of addressing global climate change. The role of soil biodiversity in regulating greenhouse gas emissions and storage of soil C is well recognized. The balance of C in soils is controlled by the interactive effects of climate, plant diversity, and soil biodiversity, and it is the soil community that ultimately controls the short- and long-term fluxes and flows of C in and out of soils. Thus, when assessing the ability of soils to store C we must also look at the specific functional types and traits within the microbial community. For example, microbial traits or functional groups that would control C cycling and storage include: C use efficiency, community biomass turnover rates, microbial produced extracellular enzymes, and stoichiometry (Bach et al. 2020).

Like three traditional levels of biodiversity (species diversity, genetic diversity, and ecological diversity), functional diversity also defined in terms of totality of genes, species, and ecosystems of a region. Trait-based approaches have shown to further advance our mechanistic understanding and predictive capabilities of the links between species traits and community responses, and thereby ecosystem processes. Here, functional diversity is represented by three main components: (1) functional richness (FRic), also known as functional biodiversity, indicates the amount of niche space occupied by the species in the community; (2) functional evenness (FEve) indicates the evenness of abundance distribution in occupied niche space; and (3) functional divergence (FDiv) indicates the degree to which the abundance distribution in functional niche space enhances divergence in functional traits within the community. Most common bacteria in the ecology of rhizosphere (functional rhizospheric diversity) include *Actinoplanes, Agrobacterium,* *Alcaligenes, Amorphosporangium, Arthrobacter, Azospirillum, Azotobacter, Bacillus, Paenibacillus, Burkholderia, Cellulomonas, Enterobacter, Erwinia, Flavobacterium, Gluconacetobacter, Microbacterium, Micromonospora, Pseudomonas, Rhodopseudomonas,* Rhizobia*, Serratia, Streptomyces, Xanthomonas,* etc. (Maheshwari et al. 2014). This is accompanied with fungal and actinobacterial communities. Fungi interact with other soil organisms and thus changes in the fungal community have the potential to affect the function of the whole soil ecosystem. Soil fungi produce a network of hyphae and as the mycelium grows the network will usually remain connected. These fungal hyphae can convert nutrients into biomass at scales ranging from millimeters to entire tracts of forest. The appreciation of all this is critical to understand the organization of fungal biodiversity in the soil and the importance of this organization to ecosystem processes. Arbuscular mycorrhizal fungi (AMF) are the most important class of beneficial microorganisms in agri- and horticultural soils. The diseases of crop plants can be controlled by some antagonistic fungi such as *Glomus* sp. or *Trichoderma* sp. suppressing fungal pathogens. Species of *Trichoderma* (*T. asperellum, T. atroviride, T. harzianum, T. virens,* and *T. viride*) are frequently used in biocontrol and are known as biostimulants for horticultural crops. A synergistic, favorable impact of AMFs and PGPRs on horticultural plant growth and soil microbial diversity and activity is also reported (Frąc et al. 2018).

18.5 Anthropogenic and Climatic Factors Influencing Soil Microbial Diversity and Functionality

Biodiversity has traditionally been defined in terms of species richness and equitability (evenness). Although the relation between species richness and ecosystem function has attracted considerable attention because of the irreversibility of species extinction, human activities influence the relative abundances of species more frequently than does the presence or absence of species, and therefore any change in species evenness warrants increased attention. Besides, changes in species evenness usually respond more rapidly to human activities than do changes in species richness and have important consequences to ecosystems long before a species is threatened by extinction (Alkorta et al. 2003). Human induced global change factors (GCFs) such as land-use change, carbon-dioxide enrichment, nutrient fertilization are accompanied with climate warming, altered precipitation, atmospheric nitrogen deposition and their combinations seriously threaten the biodiversity. The most important factors affecting the soil biodiversity comprise: changes in habitat conditions; resource availability (amount and quality of nutrients and energy sources); temporal heterogeneity (seasonal effects); spatial heterogeneity (spatial differences in the soil); climate variability; interactions within the biotic community. Land-use intensification for anthropogenic activities is increasing number of contaminated soils at global scale which is resulting in severe impacts on soil ecosystems services. In 2005, the millennial assessment of ecosystem service report noted that 60% of ecosystem services were degraded and/or used unsustainably and related this issue to pollution, habitat change, and overexploitation of natural resources among other factors. As the economic valuation of soil ecosystem services is a difficult task and often lacking at the policymaking level, the costs of services losses are going unnoticed. Consequently, the concept of ecosystem services is being considered a promising approach for environmental management and decision making. In fact, the evaluation of soil ecosystem services in environmental risk assessments of contaminants has long been advocated. Assessing ecosystem services is compatible and complementary to traditional endpoints used in environmental risk assessment for soil ecosystems (Morgado et al. 2018).

Land-use change (LUC) is the dominant driver of biodiversity decline in terrestrial ecosystems mainly through loss, degradation, and fragmentation of the habitats. Land-use intensity is constantly increasing on a global scale, with adverse effects on soil ecosystems. One quarter of soils worldwide face degradation and an increasing number of studies have shown that intensive land use threatens soil biodiversity, with some groups of soil biota severely affected in very intensive systems. On the other hand, climate change (CC) impacts soil biodiversity directly through changes in temperature and moisture, and indirectly through shifts in resource supply from plants. Combinedly, LUC and CC cause changes in the physiology and growth of individual soil organisms, leading to changes in the diversity and composition of soil communities through altered functional responses and biotic interactions. As a result, selection for new traits and life histories within soil communities will take place, which in turn drives eco-evolutionary dynamics of aboveground communities and ecological feedbacks to ecosystem processes, including greenhouse gas emissions and leaching of dissolved carbon and nutrients from soil. Land-use change is one of the greatest agents of change in soil biology and ecology and it is ubiquitous on all continents now. Thus, land-use change is rapidly and persistently altering all levels of above- and belowground interactions and acts on a large scale (Coleman et al. 2018).

Habitat loss is the primary threat to soil biota. Agriculture is the largest driver of habitat loss and biodiversity declines globally, including land conversion to agricultural use and management practices within agro-ecosystems. Land-use change with respect to crop production is happening in the form of intensive agriculture. Land-use intensification usually interferes with soil internal biological processes and, in agricultural systems, human activities often replace such internal processes with external inputs. For example, biological nitrogen fixation has sustained life on Earth for thousands of years, but modern agricultural practices are based, in huge part, on industrially produced mineral fertilizers which is replacing or severely affecting biological nitrogen fixing communities in agricultural soils. Another example is decreasing number of earthworm species in agricultural soils due to tillage and agrochemicals use. Conversion of forest to agricultural land-use results in the homogenizations of soil bacterial communities and loss of soil fungal diversity as well as reductions in macrofauna. Generally, intensive agricultural practices are considered to lead to simpler soil food webs comprising smaller-bodied organisms and fewer functional groups. Agricultural fields support smaller and less-diverse soil communities than forests and grasslands and agricultural intensification further reduces soil biodiversity, particularly larger bodied organisms (like invertebrates). Agricultural management practices, such as intensive soil tillage, repeated and intensive fertilization, application of pesticides, and low plant diversity, have been shown to have adverse effects on several groups of soil organisms, including AMF, earthworms, and microarthropods, and to reduce overall soil microbial biomass. Even reduced tillage systems typically host less soil biodiversity than natural ecosystems. Habitat quality can be degraded through pollution, including excessive nutrient inputs, and invasive species. Heavy metal pollution can shift communities to become dominated by a few taxa that can tolerate, or even thrive with, high levels of chemical inputs with corresponding decreases in taxa abundant in unpolluted soils. Increased N inputs, from atmospheric deposition or from direct fertilizer application, is also a form of pollution and can shift soil bacterial communities, decreasing *Acidobacteria* and *Verrucomicrobia* and increasing *Actinobacteria* and *Firmicutes*, and decrease overall microbial activity (Bach et al. 2020). Reduction in biological diversity of soil macrofauna is one of the most profound ecological consequence of modern agriculture.

Food security concerns and export oriented highly productive globalized agriculture systems have put pressure on land resources. Focus on high production in agricultural settings has resulted in the successive deterioration of the fundamental properties of soils, including the biological potential for self-regulation. In natural plant–soil systems, rhizosphere processes and microbial interactions are more evolved than in anthropogenic controlled cropping systems. The management practices used in many agro-ecosystems (e.g., monocultures, extensive use of tillage, chemical inputs) degrade the fragile web of community interactions between pests and their natural enemies and lead to increased pest and disease problems. In natural systems, biodiversity of the soil organisms leads to the control (natural biological suppression) of plant root diseases. Different practices cause shifts in habitat quality and in substrate availability, resulting in changes in abundance of individual species. Decline in soil biodiversity is expected to affect soil turnover, decrease natural soil aggregation, increase crusting, reduce infiltration rates, and thus exacerbate soil erosion. Many processes carried out by soil organisms persist in native ecosystems as well as in intensively cultivated soil. There is only a limited insight to what extent these changes in management intensities are accompanied by changes in spectrum of soil microorganisms responsible for the processes involved.

The agricultural factors that influence biodiversity in soils are (Fig. 18.1):

1. Intensified land use: Agriculture and its expansion have changed the diversity of habitats, and thus the number of species occurring in the environment at the landscape scale. The increasing intensity of land use also destroyed the habitat and thus has substantially decreased biodiversity. A consequence of agricultural practices is the loss of trees and surface litter and consequently of the groups of macrofauna dependant on trees and surface litter (e.g., termites, ants, soil-dwelling insect larvae). Increased use of heavy machines in agriculture leads to soil compaction, and thus to degradation of habitat for soil organisms.

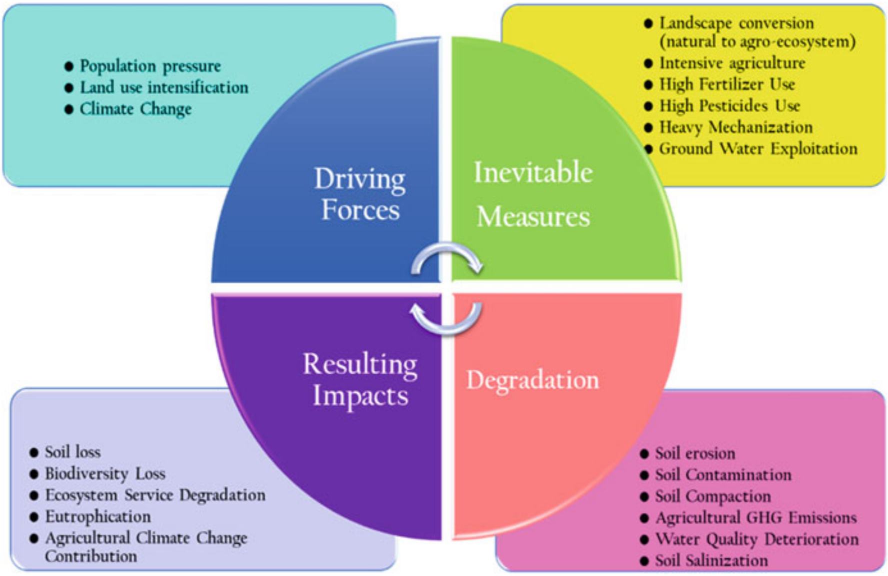

Fig. 18.1 Cause-impact relation affecting soil biodiversity and soil health (modified from Kanianska 2016)

2. Influence of cropping systems: Majority of staple crops of the world are from grass family (*Gramineae*) like rice, wheat, maize and, sugarcane. Monoculturing is practiced in their cropping systems and these crops are major consumers of chemical fertilizers. Such limited diverse systems are prone to biotic and abiotic problems. Crop rotation is a key component, which influences the composition of the soil microbial community. Systems that increase belowground inputs of C and N through inclusion of legumes or fibrous rooted crops in rotations may increase microbial populations and activities in comparison to application of commercial fertilizers. The chemical composition of crop residues may have a significant effect on the structure of decomposer communities. Similarly use of animal manure leads generally to increased abundance and activity of soil microbes.
3. Influence of type of plants: Plants have an impact on soil microbial communities through C flow and competition for nutrients. There are distinct differences in bacterial community structure between the bulk, non-rhizosphere and rhizosphere soil. Numbers of bacteria in the rhizosphere are greater than numbers in non-rhizosphere soil. Bacterial activities are stimulated in this area because of the nutrients provided by roots in the form of root exudates. The variability in chemical composition of root exudates also influences the composition of soil microbial communities.
4. Influence of fertilizers and pH: Application of fertilizers and the soil pH both influence the structure of the soil biota. Low pH favors fungi over bacteria and neutral pH favors bacteria. pH influences on soil fauna are also clear as observed in conditions of low pH in the soil resulting in decrease in the abundance of

earthworms. High nitrogen concentrations result in increased bacterial populations.

5. Influence of tillage and crop residue addition: Periodic tillage reverts soil to an earlier stage of ecosystem succession. Physical disturbance caused by tillage is a crucial factor in determining soil species diversity in the agro-ecosystem. Tillage causes the loss of stratified soil microhabitat, which results in a decreased abundance of species that inhabit agro-ecosystems. Tillage aerates the soil and there with cause rapid mineralization of organic matter along with substantial loss of nutrients. Soil tillage changes physical processes in soils and indirectly impacts diversity and activity of soil communities. Activity and diversity of soil microbial communities are influenced by availability and distribution of crop residues. Reduced tillage with surface placement of residues creates relatively stable environments, which results in more diverse decomposer communities and slower nutrient turnover. No-till system favors fungi over bacteria, as decomposition of plant residues occurs on top of the soil.
6. Pesticides application: Pesticides have both targeted and non-targeted effects that may cause a shift in the composition of the soil biota. When organisms are suppressed others can proliferate in the vacant ecological niches. The effect of pesticides strongly depends on soil physical and chemical properties, which affect their availability.
7. Influence of pollution on soil biodiversity and functioning: Pollutants in general influence the organisms living in the soil. Exposure of organisms to sublethal doses of pollutant chemical over a long time period results in progressive effects. Initially interactions occur at the level of biochemical and cellular processes and lead to physiological effects. Subsequently the structure of the DNA in organisms gets affected in the organism, leading to modification and eventual evolution of organisms. Consequently, such patterns of evolution of resistance or tolerance to the stress factors like pollutants also occur in entire communities. In soils contaminated by heavy metals the ratio of the resistant and sensitive bacteria increases in the contaminated soil, and the metal-resistant bacteria are much less effective in the decomposition of a number of organic pollutants than the trace elements sensitive bacteria. Interference of different soil stresses complicates the assessment of effects of single stress and pollutants (Breure 2004).

18.6 Microbial Integrity

Biodiversity is important for soil functioning and is reliable indicator of environmental quality. Diversity of living organisms provides best reflection of the actual fitness and ecological changes of the habitat. The diversity, abundance, and activity of soil organisms indicate the degree of sustainability of soil management. Soil microbial populations' framework of interactions is known to affect plant fitness and soil quality. They are involved in fundamental activities that ensure the stability and productivity of both agricultural systems and natural ecosystems. As discussed in previous section, climate change and land-use intensification are the two most common global change drivers of biodiversity loss. However, species differ in their responses to environmental change as well as in their effects on ecosystem functions (Yin et al. 2020). The varied genetic and functional activities of the extensive microbial populations have a critical impact on soil functions, since microorganisms are driving forces for fundamental metabolic processes involving specific enzyme activities. Many microbial interactions which are regulated by specific molecules/signals are responsible for key environmental processes, such as the biogeochemical cycling of nutrients and matter and the maintenance of plant health and soil quality.

A variety of microbial forms can be found growing in rhizosphere micro-habitats. Members of any microbial group can develop important functions in the ecosystem. However, most studies on rhizosphere microbiology, especially those describing co-operative microbial interactions, have focused their attention on bacteria and fungi. In such diversity of microbial groups, beneficial saprophytes are special as they are able to promote plant growth and health. These include (1) decomposers of organic detritus, (2) the plant growth promoting rhizobacteria (PGPR), and (3) fungal and bacterial antagonists of root pathogens. Some of these microorganisms, the endophytes, colonize the root tissues and promote plant growth and plant protection. Beneficial, plant mutualistic symbionts include the N_2-fixing bacteria and the arbuscular mycorrhizal fungi (Barea et al. 2005).

Plant community studies show positive but saturating relationship between plant biodiversity and ecosystem functioning, which can result from niche complementarity, positive interactions, greater use of limiting resources, decreased herbivory and pathogens, the presence of certain influential species, etc. Consequently, ecosystem functioning is threatened by an ongoing loss of species due to global change factors (GCFs). However, in contrast to plant communities, soil microorganisms are suggested to be too diverse and abundant to assume that the biogeochemical cycling is limited by the microbial diversity. It is still unclear whether the loss of microbial communities reduces microbial functionality in an ecosystem under GCFs as studies in these aspects are still going on. A respite in ongoing efforts to understand and relate specific functions to specific groups of microbes is advancement in functional genomic studies of soil microbes. Using array of biotechnology tools, researchers are exploring relationship of presence or absence of functional groups of microorganisms and their respective ecosystem roles.

Integrity with respect to microbial functionality and ecological processes (ecosystem services) is similar to moral integrity of standards of doing their job and determination not to lower those standards. By exhibiting or proving such integrity soil microbes show the resilience to changes that occur in their surroundings which try to influence microbial activity. Hence, microbial integrity is buffering capacity of soil microbes in maintaining soil health even in case of species extinction, species replacement, change in diversity, or community structure that are brought about by stressful conditions. Land-use change, invasive species, pollution, unsustainable soil management practices, warming and climate variabilities are all the factors that change the natural cycles of microbial multiplication and functioning. All these factors pose threat to few specialized functional communities of soil microflora like N-fixers, N transformers, decomposers, etc. and simultaneously influence common microbial communities in shifting their patterns. However, through many mechanisms like functional redundancy, tolerance to abiotic stresses, genetic exchange (to share stress-tolerant genes among related communities), adapting active-inactive life cycles according to optimal and hostile environmental conditions and/or food availability, minor mutations and through physiological modifications soil microbial communities resist environmental changes.

Traditional diversity analysis indices like microbial alpha, beta and gamma diversity can also be applied to functional groups also. Alpha diversity is number of species coexisting within a local site and beta diversity the magnitude of similarity in species composition among different sites. By studying alpha and beta diversities it is getting clear that microbial community structure is sensitive to GCFs, while GCFs affect microbial diversity inconsistently and do not always lead to the loss of microbial diversity. The relation between species richness and ecosystem function is explained by three different types of response hypotheses: (1) the measure function (production, nutrient cycling, and so on) increases continuously with increasing species richness, (2) the response is asymptotic, increasing with new species added, but at a decreasing rate, and (3) only one species of each functional type is required to maximize ecosystem function. Studies hypothesized the second response as being the most common. All three responses resonate the concept of redundancy. Although certain indications have emerged that redundancy relative to resource acquisition may be very high in most ecosystems, the diversity of the species may play a more significant role in maintaining the integrity of the ecosystems by increasing the resistance and resilience of the systems in response to disturbance. A crucial characteristic of communities with high biotic diversity is the ability either to resist disturbance or to recover rapidly from it (Alkorta et al. 2003).

Land-use intensification reduces both microbial biomass and functionality (including 16 microbial functions related to soil biogeochemical cycling). Response ratio analysis was used to understand changes in microbial community metrics due to changes in controlling environmental conditions or management practices like warming, CO_2 concentration elevation, percentage changes in precipitation-PPT^{+}/ PPT^{-}, addition rate of N or P or K, LUC types like conversion of native ecosystem to secondary ecosystem or plantation or pasture or agricultural land; all studied under field conditions for experiments with longer than 1 year/growing season. On applying response ratio analysis it was found that global change factors-induced changes in microbial alpha diversity do not mirror their functionality. Instead, significant and negative relationships are found between response ratio of microbial functionality and response ratio of microbial richness. And the negative or decoupled relationships exist within different microbial functions associated with decomposition (microbial respiration), net N mineralization rate, oxidative C-cycling enzymes, hydrolytic C-cycling enzymes, N-cycling enzymes, and P-cycling enzymes. These findings of a meta-analysis study are distinctive from the positive but decelerating richness–functionality relationship in macroecology. Potential explanation is that a consortium of microorganisms that carries out soil biogeochemical processes is characterized by a redundancy of functions; and loss of some groups of the species may have little or no effect on overall functionality because other groups can take their place. Microbial community structure is sensitive to GCFs, and a positive relationship between response ratio of community structure and functionality is observed, implying that variations in microbial community structure might play an important role in the functionality changes despite that it is difficult to tell which microbial species shifts determining the changes (Zhou et al. 2020).

Conversion from highly diverse natural ecosystems to homogeneous agricultural monocultures has a positive effect on microbial alpha diversity. Using meta-analysis of studies targeting microbial diversity changes, it is proposed that soil pH is the most important factor to predict the GCFs effects on microbial alpha diversity. Generally, if a GCF increases the soil pH, the alpha diversity would increase; if it decreases the soil pH, the alpha diversity would reduce; if it has no effect on soil pH, it would not change the alpha diversity. GCFs do not always cause microbial diversity loss like that for aboveground communities. The areas of croplands, pastures, and plantations have been expanded globally in recent decades, accompanied by large losses of the alpha diversity of plants and animals and biotic homogenization (beta diversity loss) as well. Surprisingly, LUC has a positive effect on microbial diversity of agro-ecosystems (managed ecosystems) since they promote particular group of species by narrowing the diversity through eliminating competitive pressure. This results in significant increase of alpha diversity. However, the response of overall soil functionality to GCFs can be explained by the responses of microbial community structure and biomass rather than the response of microbial alpha diversity alone (Zhou et al. 2020).

Microbes in the soil live a “feast or famine” existence, because of substrate limitations for most of the time, with only brief flushes of intense activity corresponding to those moments when substrate availability increases (for example, through the addition of plant or animal residues). Thus, most organisms in the soil are inactive or in a resting stage, especially microorganisms of which over 90% are normally resting. In this situation another question seeking answer is what the importance of structural diversity (of all species present) in relation to the functional diversity (of only the active species) is. Still more complex question in this context would be: In what way has all this specialization been achieved when most organisms are in a non-active, resting stage in soil? (Alkorta et al. 2003). It is important to note that active alpha diversity rather than total alpha diversity may be positively correlated with the ecosystem functionality, and active microorganisms compose only about 0.1–2% of the total microbial biomass. However, cautions should be taken when interpreting this notion as the microbial transition from potentially dormant to active state can occur quickly (in minutes to hours). In any case, the total biomass of microbial community is positively correlated with the microbial functions, which suggests that the whole microbial community is important for the functions. On the other hand, positive relationships between active microbial alpha diversity and functions may not be universal because there is similar alpha diversity between total and active microbial communities. In addition, concerns have been raised that not all functions are carried out by the whole microbial community; instead, some key soil functions may be carried out by specialized microbes (like ammonia oxidizer, diazotrophic, methanotrophic, phosphorus mineralizer, etc.), which may be vulnerable to diversity loss partly due to their lower richness. Studies on impacts of GCFs on both specialized microbial diversities and the functions showed significant negative relationships between response ratio of alpha diversity and response ratio of functionality for denitrifier and nitrifier, and decoupled correlations for diazotrophic and P mineralizer communities (Zhou et al. 2020).

18.7 Soil Community Composition Versus Ecosystem "Functional Microbial" Integrity

Although much is known about specific functions conducted by specific functional groups, it is unclear how widely functions are distributed among different taxa. It has been a long-held view that soil microbial communities comprise such high diversity and such a high level of functionally redundant organisms that changes in microbial community composition would not translate into changes in functioning. However, community composition is important. For example, geographically distinct microbial communities have distinct rates of carbon mineralization. Agricultural land-use systems usually have a lower (sometimes much lower) level of soil biodiversity compared with less intensively used or natural ecosystems. Therefore, the loss of a small number of species or functional groups in such systems could more easily hamper ecosystem functions compared with natural ecosystems. The functional capabilities of less-diverse soil communities were less resistant to stress compared with diverse communities. Some ecosystem functions are provided by microbial consortia and different functional groups of soil biota have been shown to complement each other in supporting plant productivity. Hence, simplification of soil food webs and the loss of particular soil biota can directly and indirectly affect the functioning of remaining soil biota. Soil health depends mainly on the maintenance of four major functions, which in turn are determined by a combination of different biological processes: (1) carbon transformations, (2) nutrient cycling, (3) soil structure maintenance, and (4) biological population regulation. The biological processes contributing to these functions are provided by a set of key functional groups of soil living organisms (Morgado et al. 2018).

Wagg and his team manipulated the soil biodiversity and community composition by filtering soil through different meshes of declining size (Wagg et al. 2014). A successive reduction in soil biodiversity led to the successive decline in some of the measured ecosystem functions, such as plant diversity. Other functions, such as litter decomposition, were maintained at a constant degree at higher levels of biodiversity but declined sharply after a certain mesh size, indicating that the performance of this function depends on particular groups of organisms (represented as keystone species). Similarly, Schimel proposed to categorize ecosystem functions into physiologically and phylogenetically narrow (e.g., nitrification) and broad processes (e.g., organic matter decomposition). For some functions, soil biodiversity per se seems to be important, while for others, the presence of certain organism groups (soil community composition) is crucial. For the proper functioning of ecosystem processes, a basic toolbox of organisms with certain functional characteristics is necessary, while further increases in soil biodiversity give no direct benefits, suggesting functional redundancy among species (Ramsey et al. 2005). This imposes the difficulties of applying a unifying concept (of soil biodiversity) to different ecosystem functions, because the underlying mechanisms are likely to vary from function to function. Even then, the stochastic effects of soil biodiversity directly provide benefits for ecosystem functioning. Studies investigating soil biodiversity–ecosystem functioning relations found that at low levels of soil biodiversity, additional species often improved ecosystem functioning, while at higher diversity levels, effects of species richness on functioning were less frequent. Such studies also showed that community composition often had stronger effects compared with species richness. With changing environmental conditions, through climate variations, the ability of a particular organism to perform its function might be hampered. With high biodiversity, the probability is higher that a partly redundant organism can take over the function under the new environmental conditions (insurance effect of biodiversity). Nevertheless, to maximize the beneficial effects of soil organisms on ecosystem functioning, both soil biodiversity per se and the presence of specific key organism groups have important roles, depending on the function considered.

Structural changes in natural soil communities do not necessarily lead to functional losses. However, in some situations, these changes might be regarded as early warnings of potential impairments in soil ecosystem functioning. Regarding the possible relation between species diversity and ecosystem function, two hypotheses, each assuming a positive link, are known: the “rivet” hypothesis, which suggests that each species has a unique effect on ecosystem function, and the “redundant species” hypothesis, which suggests that only a minimum number of species is necessary for ecosystem function. Neither the “rivet” nor the “redundant species” hypothesis realistically mimics nature because of species specific differences in the strength of their effects on ecosystem functions. In this context, the definition of ecosystem function (ecosystem processes and ecosystem stability) is not always straightforward. Besides, when discussing biodiversity and ecosystem functioning, the term *functioning* means “showing activity” and does not imply that the organisms are performing purposeful roles in ecosystem-level processes. All species are not alike in terms of their importance to maintaining function, and removing the keystone species from the system can lead to major alterations in structure and function. For example, mycorrhizal fungi can play the keystone role in controlling the distribution of woody plants at the edges of forested regions (Alkorta et al. 2003).

The interplay between community structure and functioning has been the favorite subject of research and intense debate among soil ecologists. Soil communities have a high level of redundancy between species. For this reason, it is normally assumed that small to moderate changes in soil ecosystem structure can be accommodated by the presence of a high number of species with similar roles within the community. Soil functioning is thought to be unaffected by structural changes until the tipping point is reached, where the ecological role of some species or groups of species cannot be compensated by any others still present in the community. Therefore, soil biodiversity works as an insurance against potential disturbing events. A vast number of experimental studies performed in soil ecosystems have proved the "redundant species" hypothesis, leading to the general belief that functional endpoints are less sensitive than structural endpoints for the assessment of environmental integrity. Focusing only on soil functions may allow the protection of vital soil processes but gives little indication of the effects on soil communities. Although convenient from an anthropocentric point of view, soil biodiversity should have an intrinsic value that would be worth conserving. Understanding how structure affects functioning is essential for long-term soil monitoring and management. As alternative hypothesis ("rivet" hypothesis) states that any species loss, to any extent, always leads to an ecosystem function decrease because every species holds a specific contribution to the functioning, and this contribution is eliminated from the system in case of species removal. This hypothesis assumes that ecosystem functioning decreases linearly with increasing species loss. Such linear responses have been less frequently documented in soil ecosystems. In natural conditions it is difficult to find evidences of functional redundancy when comparing the results of functional endpoints (like soil respiration, soil microbial biomass, above-, and belowground plant biomass) with changes in microbial community structure as observed by Ramsey et al. using phospholipid fatty acids analysis, along a long-term metal contamination gradient. Both structural and functional endpoints were nonresponsive at low contamination levels but increased linearly toward higher levels of contamination. Further, contrary to normally assumed redundant approach, functional endpoints were more sensitive than structural ones because the linear increase started at low contamination levels. Hence an additional third theory, the "idiosyncratic" hypothesis states that no relationship exists between changes in soil community structure and soil functioning. Idiosyncratic hypothesis suggests that not all species have equal contribution to ecosystem processes (as key functional groups may have disproportionate importance) and, therefore, species richness does not always provide insight into soil functioning (Morgado et al. 2018).

18.8 Promotion of Soil Biodiversity to Enhance Agricultural Sustainability

Soil biota are of pivotal importance for nutrient and carbon cycling in both natural and agricultural ecosystems. Soil fauna fragments the organic matter, while saprotrophic fungi and bacteria decompose, making organically bound nutrients available for further processing through the entire soil food web and for plant uptake. Among beneficial fungi, plant-symbiotic arbuscular mycorrhizal fungi (AMF) can reduce not only the amount of plant nutrients leached from soil, but also the amount of N_2O emitted from soil through denitrification. Soil biological processes determine the potential of soils to sequester carbon. The potential for carbon sequestration increases with higher proportions of fungi in soil as they are slow multipliers with higher biomass as compared to bacterial groups with quick succession. An overall increase in soil fauna increases plant productivity up to 35% across ecosystems, and bacterivorous microfauna were found to contribute to enhanced plant nutrition. Similarly, earthworm abundance is generally related to enhance crop yields. Although the soil fauna has been shown to have profound impacts on soil ecosystems and to regulate many important soil processes, the key steps in the major elemental cycles are ultimately conducted by soil microorganisms. Various processes in the nitrogen cycle are exclusively performed by microbes (e.g., fixation of atmospheric nitrogen into plant available ammonium; nitrification of ammonium into nitrogenoxides; or denitrification of NO_3 into N_2O and N_2). These processes are of key importance for ecosystem functioning because the availability of nitrogen determines plant productivity and excess nitrogen can cause environmental problems, such as water eutrophication, decreased water quality, global warming, depletion of the stratospheric ozone layer, among others. Thus, enhanced soil biodiversity and specific changes in soil community composition can complement each other to increase overall ecosystem sustainability and ecosystem stability, in terms of the long-term, environment friendly delivery of crucial ecosystem services.

As discussed earlier, high biodiversity always benefits crop growth and production along with ensuring sustainability and environmental safety. All the common management approaches that promote higher levels of biodiversity are helpful in ensuring healthy soil conditions and even further help crop plants to cope with environmental stress factors. Crop diversification, organic farming, integrated nutrient management approaches, conservation tillage, minimal tillage practices, resource conservation techniques (mulching, green manuring, residue recycling), biocontrol methods, biofertilizers application, and other practices that reduce exploitation of soil and at the same time improve its quality are considered beneficial management practices for functional microbial diversity management (Saha et al. 2017). Ecological intensification of soils and soil biological engineering are few new promising concepts to enhance usage of internal ecosystem processes for sustainable soil management and through targeted management of soil community composition. Some strategies to enhance microbial diversity of agro-ecosystems are discussed below (Bender et al. 2016).

18.8.1 Soil Biodiversity Engineering

Interventions in natural processes are necessary to maximize benefits from ecosystems for human requirements. Blindly enhancing soil biodiversity infers random inclusions of more species and maintaining more of everything in an unspecified manner might also include greater diversity of undesired organisms, such as pathogens or weeds. Thus, instead of general approach targeted enhancement of consortia of microbes capable of organic matter decomposition, plant growth promotion, plant hormone production, siderophore production, metal transformation (to plant available form), nitrogen fixation, and pathogen suppression should be followed. To achieve maximum effects, management strategies must apply at multiple scales, from soil and plant community management to plant genetic and rhizosphere microbiome management. At entry point for management crop, plant choice should consider enhanced crop diversity, intercropping, living mulch, including N-fixing legumes, diverse rooting patterns, mixing perennial and annual and other factors. At another entry level of soil management mulching, reduced soil tillage and no-till should be given priority. At microbiome level, rhizosphere microbiome management like nitrification inhibition or denitrification inhibition, disease suppression, inoculation with beneficial soil organisms (such as plant growth-promoting bacteria), fostering indigenous AMF communities or inoculation with AMF shall be considered.

18.8.2 Soil Management

Practices that conserve the soil biological potential while allowing economic farm management are important in promoting biodiversity. Conventional mechanized/heavy tillage often has adverse effects on soil biota and promotes the decomposition and mineralization of organically bound nutrients even though it eases weed control. Hence, practices that minimize negative effects on soil biota while providing the desired agricultural benefits (like no or reduced soil tillage, and strip tillage) need to be followed. Such conservation tillage practices are often most successful in combination with other measures, such as cover crops and mulches. The application of organic residues and composts has also been shown to reduce pest incidence and weed pressure, and to favor soil biota. In addition to organic manures, the application of biochar to agricultural soils has received much attention in the past decade as biochar improves soil physical/chemical properties and plant performance. Practices conserving the soil biological potential can enhance or maintain soil organic matter content and, therefore, can contribute to long-term soil preservation.

18.8.3 Efficient Crop Diversification

Species mixtures and crop rotations favor higher soil biodiversity and make use of complementary biodiversity effects. Spatial crop diversification (intercropping) or temporal crop diversification (crop rotation or cover crops or relay crops) has proven to have several beneficial effects on ecosystem processes. Specific cover crops enhance the abundance of soil biota that increase the yield of the subsequent crop. Planting diverse mixtures of cultivars reduce pathogen incidence. There is a lack of studies addressing beneficial effects on soil biota and belowground ecosystem processes through enhanced crop diversity in an applied agronomic context except few studies comparing effect of grass family crops (rice, wheat, maize, etc.) and legume family crops (cow pea, alfalfa, soybean, etc.). The targeted combinations of crop varieties with different traits in relation to ecosystem functioning also exploiting niche complementarity effects theoretically opens up a range of possibilities to manage ecosystem services in cropping systems and to reduce the dependence on external resource inputs.

18.8.4 Plant Breeding for Rhizosphere Microbiome Engineering

It is now well understood that plants can shape their root endophytic and rhizospheric microbial communities through root exudates and selective promotion and/or inhibition of microbial species. This feature theoretically provides the option to breed crops to acquire soil microbes that provide specific services. For example, some plants can inhibit the transformation of ammonium into nitrate (nitrification) by affecting nitrifying microbes. This potentially improves the nitrogen availability of the plant and can also reduce nitrogen losses from soil through leaching and denitrification. The integration of knowledge about how plants regulate the composition of the root microbiome into crop breeding strategies could greatly contribute to agricultural sustainability. For example, the recruitment of root symbionts, such as AMF or rhizobia, is mediated through carbon allocation and root exudation of specific compounds. Selecting crops for the high production of such compounds could maximize symbiotic benefits. Selection for the plant microbiome can also contribute to disease suppression or to altered plant traits, such as flower time. Plant breeders have largely ignored such processes and it is now a key challenge to integrate root traits and associate microbiomes in future breeding programs, especially since several modern plant cultivars have partly lost their ability to associate with beneficial soil biota. Action is urgent because the development of new cultivars is often time consuming and can take decades, especially if multiple traits are involved. The adoption of transgenic methods could also be an option to engineer plant effects on rhizosphere communities.

18.8.5 Biofertilizer/Effective Microbe Application and Biocontrol

Plant nutrition contributing or supplementing microorganisms are well recognized and are being used also to considerable extent. Bio-stimulating stress enhancing microbes are being promoted as "effective microbes (EMs)" very recently. Several groups of such organisms are identified, and their mechanisms of plant growth promotion (other than direct nutrient supplementation) and biotic/abiotic stress tolerance are being elucidated regularly. Maximum utilization of these groups of microbes along with regular well known biofertilizers (N-fixers, PGPR, P-solubilizers) as consortia will help plant establishment and enhanced production (Fig. 18.2). Inoculation of seedlings or soils with AMF propagules is, in addition to fostering indigenous AMF communities, an option to profit from beneficial effects provided by these fungi. The use of biocontrol agents to control agricultural pests is much appreciated approach. However, due to lack of biocontrol agents for vast number of insect pests and easy availability of broad-spectrum insecticides, these chemicals are being used excessively to save crops from pest and disease attacks. A range of microbial phyla, such as *Pseudomonas*, *Bacillus*, and *Trichoderma*, can induce systemic resistance of plants against pathogen attacks. Recent developments in sequencing-based methods from soil or root samples to identify species and even

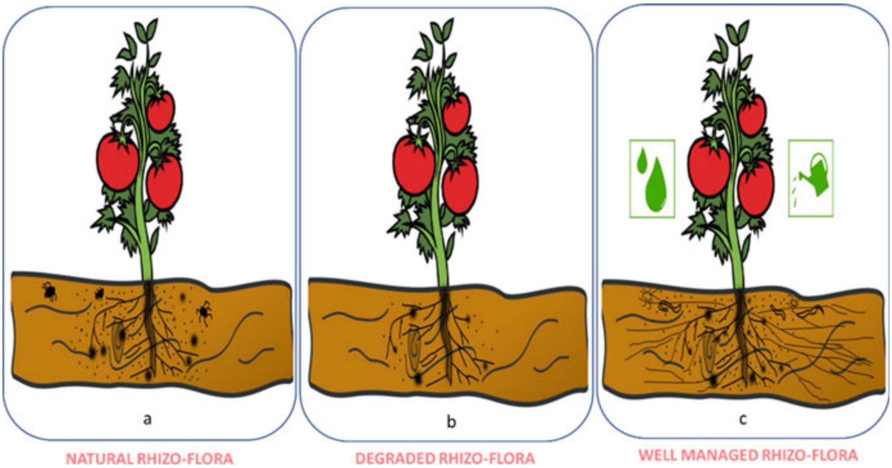

Fig. 18.2 Rhizosphere microbiome engineering concept (Comparison of three of rhizosphere organization conditions: (**a**) Natural ecosystem rhizosphere with normal density of flora, fauna, root- exudates, microbial numbers; (**b**) Degraded ecosystem rhizosphere such as intensive agro-ecosystems with high fertilization, chemical application, and heavy mechanization; (**c**) Well managed rhizosphere through ecological intensification concept through inoculation with microbial consortia, AMF, beneficial fungi, earthworms with application of organic nutrient source under minimal soil disturbance. Adopted from Wallenstein 2017)

specific isolates will make it possible to follow the fate of microorganisms introduced into soils and will allow risk assessment.

18.9 Conclusions

Proper soil functioning now and in the future is a key life support function and soil biodiversity is important because of their role in ecological functions like soil structure formation, maintaining stability of soil structure and functions, fertility, buffering and in providing possibilities to have the soil acting as a carbon sink. Living communities—soil biodiversity—within soil drive the processes central to plant growth, directly impacting human health and well-being through crop and livestock forage production. Growing concern is to attain sustainable agricultural use of soils. In agro-ecosystems ecological functioning of the soil can be seen as a production support function of biodiversity. There is increasing consensus, that protection of the biodiversity in the soil is a major way to maintain the proper functioning of the soil. Conservation agriculture and organic farming approaches attempt to reduce negative impacts on biodiversity and soil biota. However, more sustainable land-use systems do not achieve yield levels of intensive systems. It appears that optimization of supporting services, such as nutrient cycling or soil formation, trades off with provisioning services, such as crop yield. Given the constantly growing human population and changes in human diet towards higher meat consumption, food production will have to be doubled within the next few decades. Therefore, yield declines through trade-offs between supporting and provisioning services will have to be minimized. A major challenge for the next decades will be to develop strategies and tools to optimize sustainability while maximizing yields. Majority of soil biodiversity research examines diversity at a community level, across species and trophic levels; however, diversity within species is a critical component of biodiversity which has been all but ignored in soil habitats. Although microorganisms are perhaps the most diverse and abundant type of organism on Earth, the distribution of microbial diversity at continental scales is poorly understood. Soil bacterial communities do exhibit biogeographical patterns at the continental scale of inquiry and that these patterns are predictable (Fierer and Jackson 2006) and studies at continent or biome level are very few.

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19 The Effect of Crops and Farming Systems on Soil Quality: A Case Study

Anupam Das, Debashis Dutta, and A. S. Panwar

Abstract

Sustainable production systems are essential for food and livelihood security and imperative to upkeep soil health and subsequently ponder over environmental degradation. Viable option is the ecologically sustainable practice and environmentally-benign science-led diversification in a farming system mode, i.e. the so-called integrated farming system. This system has an edge over traditional cultivation, in respect of water productivity, energy and input use efficiency along with regular income generation to meet farmers' daily needs. Technological options are available on maximization of yield of different components concerning crops (cereals, vegetables, fruits, flowers, oilseed, pulse crops, etc.), livestock, poultry, fisheries, etc. besides its climate-resilient nature. Thus, small and marginal farmers will be worst affected, as they are solely dependent on farming for their livelihood. But, the major challenge before the scientific community is to develop environmentally-benign, climate-resilient models for ensuring livelihood of the small and marginal farming families.

Keyword

Integrated farming system · Soil quality · Climate resilience · Livelihood security

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19.1 Introduction

Soil is a thin layer over the earth surface and performs many processes essential to the life. It serves as a medium for supporting plant growth, as a nutrient reservoir, and as the site for many biological processes involved in decomposition and recycling of plant and animal products (Wienhold et al. 2006). Soil integrates, transforms, stores, and filters material relevant to its environmental and management conditions in the spatial context (Dalia 2008). It is also a medium that is challenged by changing environmental and management conditions, therefore variable in time as well (Toth et al. 2007). Soil resource is non-renewable in human time scales (Jenny 1980). The components of soil include inorganic mineral matter (sand, silt, and clay particles), organic matter, water, gases, and living organisms such as earthworms, insects, bacteria, fungi, algae, and nematodes (Fageria 2002). Soil resources provide the starting point for successful agriculture (Gowing and Palmer 2008). In fact, no agricultural system can be claimed to be sustainable without ensuring the sustainability of soil quality (Arshad and Martin 2002). Therefore, soils must be managed so that they remain resilience to environmental forces and stresses that are a result of farming itself, and this can only be achieved by balancing outputs from the soils with input to it (Parr et al. 1992; Sharma et al. 2005). It is increasingly acknowledged that sensible use of soil resource is essential to feed the growing world population, promote sustainable development, maintain local, regional, and global environmental health (Arshad and Martin 2002; Gowing and Palmer 2008). Past management of agricultural and terrestrial ecosystems to meet the needs of increasing human population has taxed the capacity and resilience of soil and ecosystem functions to maintain the global balance of energy and matter (Doran and Parkin 1994; Moebius et al. 2007). Worldwide deforestation, overgrazing, and conversion of rangelands have resulted in a great decline in the physical, chemical, and biological quality of soil resources (Doran 1999). Therefore, many soils have been worn down to their nadir for most soil parameters essential for effective, stable, and sustainable crop production (Moebius et al. 2007; Kibblewhite et al. 2008). In consequence, soil degradation or changes in soil quality (SQ) is emerging as an environmental, economic, and policy issue of increasing global trend (Cécillona et al. 2009; Rakshit et al. 2018). The inability to identify poor cropping systems and management practices in agricultural areas has resulted in problems of soil erosion, compaction, acidification, organic matter losses, desertification, reduction of fertility and productivity, chemical contamination, which have reduced agricultural production capacity and food security (Schindelbeck et al. 2008; Sant'anna et al. 2009).

As new questions and concerns arise about our ability to sustain our limited land and water resources, the importance of adequate assessment tools for evaluating the effects of land management practices on soil, air, and water resources grows (Zobeck et al. 2008). Therefore, there is an urgent need to identify suitable indicators to monitor changes in soil quality due to land use and management practices (Larson and Pierce 1991; Doran and Parkin 1994; Masto et al. 2008; Zobeck et al. 2008; Gartzia-Bengoetxea 2009; Jokela et al. 2009; Subhadip et al. 2019). There are potentially many soil properties, which might serve as indicators of soil quality and research is required to identify the most suitable one. It is against the introduction provided so far, that this paper discusses the concept of soil quality, its indicators and assessment procedures.

19.2 Soil Quality

Conceptual definitions of soil quality are still evolving and present definitions of soil quality vary depending on the views and the background of individuals. Traditionally, soil quality was equated with various soil properties that contribute to soil productivity, which is the capacity of a soil to produce a plant or sequence of plants under a given management systems. However, mere analysis of soil properties alone, no matter how comprehensive or sophisticated, cannot provide a measure of soil quality unless the properties evaluated are calibrated or related against the designated role or function of the soil (Giuffre et al. 2006). Thus, implicit in recent definition and assessment of soil quality is an understanding of the stated function of the soil or what the soil does (Doran and Parkin 1994; Karlen et al. 1997).

Anderson and Gregorich (1984) proposed that soil quality be defined as "the sustained capability of a soil to accept, store and recycle water, nutrients and energy". However, agriculture is now viewed as part of a much broader ecological system, which interacts with, and affects other various parts of the system. This development is expressed in the expanded concept of soil quality evident in the work of Larson and Pierce (1994). They define soil quality "as the capacity of a soil to function within its ecosystem boundaries and interact positively with the environment external to that ecosystem". This definition also recognizes that soil serves other functions both within and beyond agricultural ecosystems. A more detailed definition has been developed by the Soil Science Society of America (1995) as follows: "Soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". This definition is similar to that of Doran and Jones (1996) where soil quality is the "capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal and human health".

The concept of soil quality is closely related to that of soil health, which is widely used within discussions on sustainable agriculture to describe the general condition or quality of the soil resource. For instance, Kibblewhite et al. (2008) proposed a definition of soil health as follows: that a healthy agricultural soil is one that is capable of supporting the production of food and fibre, to a level and with a quality sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity'. Idowu et al. (2007) remarked that the term "soil quality" is more favoured by scientists, whereas "soil health" is a term favoured by farmers as it connotes a holistic approach to soil management.

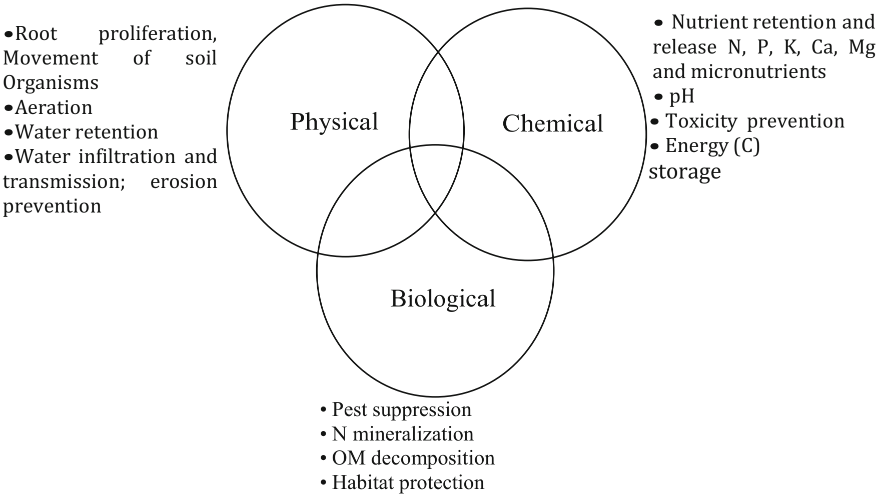

Fig. 19.1 Soil physical, chemical, and biological processes and functions

Figure 19.1 shows that soil health is a composite picture of the state of the soil's physical, chemical, and biological properties. Therefore an important issue in soil quality/health is the integration of the chemical, biological, and physical processes and functions (Dexter 2004; Idowu et al. 2007; Idowu et al. 2008).

19.3 Integrated Farming System

An integrated farming system consists of a range of resource-saving practices that aim to achieve acceptable profits and high and sustained production levels, while minimizing the negative effects of intensive farming and preserving the environment. Based on the principle of enhancing natural biological processes above and below the ground, the integrated system represents winning combinations that (a) Reduces erosion, (b) Increases crop yields, soil biological activity and nutrient recycling, (c) Intensifies land use, improving profits and therefore help to reduce poverty and malnutrition and strengthen environmental sustainability. Livestock and crop production systems are an integral part of one another (Kallah and Adamu 1988). Crop residues provide fodder for livestock while, occasionally, grain provides supplementary feed for productive animals. Animals improve soil fertility through manure and urine deposition and animal power for farm operations and transport. Sale of animals sometimes provides cash for farm labour and agricultural inputs. There are several examples of completely integrated crop–livestock production systems where sustainable increases in both crop and livestock production have been achieved after considerable periods (30–40 years) of continuous cropping without resulting in land degradation. Some of them are the close settled zone

(CSZ) of Kano in northern Nigeria (Harris 1995), Banamba in Central Mali (Abou Berthe, personal communication), and Batalay in southern Chad.

The key success to these farming systems is effective crop–livestock integration involving the recycling of nutrients within the system. A particular challenge facing farmers is to minimize nutrient losses through good management; improved feed production, quality, availability, and more efficient feeding systems; new ways to capture and conserve nutrients excreted by livestock; improved manure spreading techniques; and cropping systems that reduce nutrient losses and can improve livestock impacts on the soil environment.

19.3.1 Key Principles

19.3.1.1 Cyclic

The farming system is essentially cyclic (organic resources – livestock – land – crops). Therefore, management decisions related to one component may affect the others.

19.3.1.2 Rational

Using crop residues more rationally is an important route out of poverty. For resource-poor farmers, the correct management of crop residues, together with an optimal allocation of scarce resources, leads to sustainable production.

19.3.1.3 Ecologically Sustainable

Combining ecological sustainability and economic viability, the integrated livestock-farming system maintains and improves agricultural productivity while also reducing negative environmental impacts. Some lessons learned and recommendations are:

- The maintenance of an integrated crop–livestock system is dependent on the availability of adequate nutrients to sustain animals and plants and to maintain soil fertility. Animal manure alone cannot meet crop requirements, even if it does contain the kind of nutrients needed. This is because of its relatively low nutrient density and the limited quantity available to small-scale farmers. Alternative sources for the nutrients need to be found.
- Growing fodder legumes and using them as a supplement to crop residue is the most practical and cost-effective method for improving the nutritional value of crop residues. This combination is also effective in reducing weight loss in animals, particularly during dry periods.
- Given their traditional knowledge and experience, local farmers are perfectly able to apply an integrated system. In practice, however, relatively few adopt this system, mainly because they have limited access to credit, technology, and knowledge. The crop-pasture rotation system is complex and requires a substantial capital outlay for machinery and implements. Associations of grain and

livestock producers are useful for filling these gaps and can promote the adoption of a crop–livestock system.

- Better livestock management is needed to safeguard water. Livestock water demand includes water for drinking and for feed production and processing. Livestock also have an impact on water, contaminating it with manure and urine. All of these Indian Research Journal of Extension Education, Special Issue (Volume II), 2012 51 aspects need to be given due to consideration.
- Intensification of agriculture through appropriate incorporation of small livestock has the potential to decrease the land needed for agricultural production and relieve the pressure on forests.

19.3.1.4 Advantages

Economic analysis of different farming systems (one hectare of irrigated land or 1.5 ha of unirrigated land) indicated that under irrigated conditions, mixed farming with crossbred cows yielded the highest net profit, followed by mixed farming with buffalo, and arable farming. Mixed farming with Hariana cows made a loss (Singh et al. 1993). Comparative productivity and economies of dairy enterprises (mixed farming with three crossbred cows on one hectare of canal-irrigated land versus mixed farming with three *Murrah* buffalo) indicated that mixed farming with crossbred cows under canal-irrigated conditions was more efficient for the utilization of land, capital, inputs, and the labour resources of the farmer (Kumar et al. 1994). Baseline surveys in Gujarat, India indicated that around 75 per cent of rural households kept cattle in the face of underemployment. More particularly, the farm surveys showed that cattle kept mainly for milk, contributed 32 per cent and 20 per cent for tribal and non-tribal ethnic groups, respectively (Patil and Udo 1997). By comparison to cows and buffaloes, lactating goats contributed between 54 and 68.9 per cent to total farm income through the sale of milk (Deoghare and Bhattacharyya 1993, 1994; Deoghare and Sood 1994). The significance of milk production from goats and the links to food security and livelihoods of the poor has recently been reviewed (Devendra 1996). In an integrated system, livestock and crops are produced within a coordinated framework (van Keulen and Schiere 2004). The waste products of one component serve as a resource for the other. For example, manure is used to enhance crop production; crop residues and by-products feed the animals, supplementing often inadequate feed supplies, thus contributing to improved animal nutrition and productivity.

The result of this cyclical combination is the mixed farming system, which exists in many forms and represents the largest category of livestock systems in the world in terms of animal numbers, productivity, and the number of people it services. (van Keulen and Schiere 2004).

Animals play key and multiple roles in the functioning of the farm, and not only because they provide livestock products (meat, milk, eggs, wool, and hides) or can be converted into prompt cash in times of need. Animals transform plant energy into useful work: animal power is used for ploughing, transport and in activities such as milling, logging, road construction, marketing, and water lifting for irrigation.

Animals also provide manure and other types of animal waste. Excreta have two crucial roles in the overall sustainability of the system:

a. *Improving nutrient cycling*: Excreta contain several nutrients (including nitrogen, phosphorus, and potassium) and organic matter, which are important for maintaining soil structure and fertility. Through its use, production is increased while the risk of soil degradation is reduced.
b. *Providing energy:* Excreta is the basis for the production of biogas and energy for household use (e.g. cooking, lighting) or for rural industries (e.g. powering mills and water pumps). Fuel in the form of biogas or dung cakes can replace charcoal and wood. Crop residues represent the other pillar on which the equilibrium of this system rests. They are fibrous by-products that result from the cultivation of cereals, pulses, oil plants, roots, and tubers. They are a valuable, low-cost feed resource for animal production, and are consequently the major source of nutrients for livestock in developing countries. The overall benefits of crop–livestock integration can be summarized as follows:
   - Agronomic, through the retrieval and maintenance of the soil productive capacity;
   - Economic, through product diversification and higher yields and quality at less cost;
   - Ecological, through the reduction of crop pests (less pesticide use and better soil erosion control); and.
   - Social, through the reduction of rural urban migration and the creation of new job opportunities in rural areas.

   This system has other specific advantages

- It helps improve and conserve the productive capacities of soils, with physical, chemical, and biological soil recuperation. Integrated Crop–Livestock farming system: Key aspects Animals play an important role in harvesting and relocating nutrients, significantly improving soil fertility and crop yields.
- It is quick, efficient, and economically viable because grain crops can be produced in 4–6 months, and pasture formation after cropping is rapid and inexpensive.
- It helps increase profits by reducing production costs. Poor farmers can use fertilizer from livestock operations, especially when rising petroleum prices make chemical fertilizers unaffordable.
- It results in greater soil water storage capacity, mainly because of biological aeration and the increase in the level of organic matter.
- It provides diversified income sources, guaranteeing a buffer against trade, price and climate fluctuations.

One key advantage of crop–livestock production systems is that livestock can be fed on crop residues and other products that would otherwise pose a major waste disposal problem. For example, livestock can be fed on straw, damaged fruits, grains, and household wastes (Fakoya 2017). Integration of livestock and crop allow nutrients to be recycled more effectively on the farm. Manure itself is a valuable fertilizer containing 8 kg of nitrogen, 4 kg of phosphorus, and 16 kg of potassium to the tone (FAO 1999). Adding manure to the soil not only fertilizes it but also improved its structures and water retention capacity (ILCA 1998; FAO 1996) opined that where livestock are used to graze, the vegetation under plantations of coconut, oil palm, and rubber, as in Malaysia, the cost of weed control can be dramatically reduced, sometimes by as much as 40%. In Colombia sheep are sometimes used to control weeds in sugarcane. Draught animal power is widely used for cultivation, transportation, water lifting, and powering food processing equipment. Using draught animal reduces the need for foreign exchange to buy expensive tractors and fuel (Jahake 1992). According to International food security treat Campaign (1984) it was estimated that 52% of the cultivated area in developing countries excluding China is farmed exclusively with draught animal, animal traction, bringing heavy but potentially very productive soil into production. According to FAO (1997), cow dung is widely used for used for cooking and heating in many countries. Alternatively, 25 kg of fresh cow dung makes on cubic metre of biogas, which can be used to provide energy for light, heat or motive power.

Case studies on Integrated farming system and Soil quality:

The integration of crops and livestock is not a new technology; rather, it is a re-emerging concept. Since the domestication of plants and animals, there is evidence that integrated crop–livestock systems where the most common pattern in the Neolithic age when humans first gathered into small village and farmstead groups. Crop production was probably first combined with animal husbandry 8–10 millennia ago (Russelle and Franzluebbers 2007). In Latin America, integrated crop–livestock systems originally were used to establish pastures in a rotational sequence beginning with a grain crop, usually rice (Oryza sativa L.), to take advantage of the increased fertility in the short term after clearing forested land (Entz et al. 2005).

Crop successions must maintain on average over 6 Mg/ha dry matter in crop residues within rotations (Landers 2007). However, most rotations are not capable of maintaining that minimum level of crop residue on the soil. Salton (2007) reported that crop rotations have had negative carbon balance, and continuous cropping is not able to increase, nor maintain, soil carbon stocks. According to Landers (2007), incorporating pastures and animals in rotation with crops cultivated in no-tillage systems optimizes even more the beneficial characteristics of conservation agriculture, particularly via the capacity of pastures to sequester carbon (Salton 2007), but also by increasing biodiversity, improving nutrient cycling, and reducing economic risk (Moraes et al. 2007).

Russelle and Franzluebbers (2007) stated that multiple agronomic and environmental benefits can be realized when land is converted from low diverse cropping systems to rotations that include forages. The author cited Randall et al. (1997) and Shiftlet and Darby (1985) to illustrate that introduction of perennial crops into previous annual crop systems reduces the risk of environmental damage during the cropping phase by decreasing nitrate leaching up to 96% and nearly eliminating soil erosion by water. Lemaire et al. (2003) cited that pastures have analogous effects as forests and can help agricultural systems regulate environmental fluxes to achieve multiple environmental benefits through positive effects with regard to: (1) hydrological impacts and maintenance of surface and subterranean water quality; (2) carbon sequestration; (3) nitrogen flux regulation; (4) gas emission regulation (N_2O, NH_3, CH_4 . . .); (5) organic matter stability and soil quality maintenance; (6) stimulation of soil biological activity; (7) immobilization and retention of pesticides and heavy metals. Concerning the integration of pastures in crop rotations in southern Brazil, Moraes et al. (2002) reported several advantages, including maintenance of physical, chemical, and biological soil characteristics, erosion control, more efficient use of natural resources and pollution control. In addition, the authors mentioned improvements in crop protection, increased animal and crop production, greater economic returns, better weed control, and break in disease and insect cycles. Indeed, Costa and Rava (2003) reported a 75% reduction in *Rhizoctonia* and *Sclerotinia* bean infections using rotations with perennial tropical forages. Integrated crop–livestock systems can increase biodiversity via the attributes of organic matter provided by pastures (Lemaire et al. 2003). The resulting flora and fauna diversity, as well as microbial and faunal soil communities, change the soil and its physio-chemical properties (Lemaire et al. 2003).

The pastoral environment is particularly important to the colonization/extinction of many organisms (e.g. insects, mollusks) and is a forage resource for many birds and mammals, frequently being their reproduction site. For these reasons, Lemaire et al. (2003) consider pastures essential for biodiversity maintenance at the landscape level, being the habitat of invertebrates that are important to carbon and nitrogen cycles. Despite the potential benefits reported for crop–livestock integration, this technology can only be successful if some basic concepts are followed. According to Moraes et al. (2002) some of the key principles that must be adopted include: (1) no-tillage, (2) crop rotation, (3) nutrient inputs, (4) improved animal and crop genetics, and (5) sound grazing management. From all those requirements, the pasture phase and related grazing management is commonly considered to be essential in defining the nature and intensity of potential relationships.

Sustainable development is the only way to promote rational utilization of resources and environmental protection without hampering economic growth and integrated Farming Systems hold special position as in this system nothing is wasted, the by-product of one system becomes the input for other. India has a considerable livestock, poultry population, and crop wastes. All efforts have to be mobilized to reclaim the resources and to put them to use effectively. Suitable technology has to be developed for the treatment of wastes and their all-round effective utilization, so that, it can help in to reducing the poverty and malnutrition and strengthen environmental sustainability. The highly improved integrated crop–livestock system can guarantee more sustainable production and therefore constitutes a valid new approach. The soil is the central component of the processes that indicate the direction of such modifications. The catalysing component is the animal, which recycles the vegetative material and modifies the dynamics of nutrient cycling when compared with systems where winter cover crops are grown solely for production of plant residues for soil cover. When grazing livestock were integrated into a cash crop rotation, and when this was done using moderate, controlled grazing intensities, soil aggregation was significantly improved, as well as the soil microbial activity. Positive impacts were also observed in the chemical attributes of associated variables, such as total and particulate organic carbon and nitrogen, phosphorus availability and potassium cycling and balance, hence improved soil quality could be ensure.

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Liquid Biofertilizer: A Potential Tool Towards Sustainable Agriculture

20

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Abstract

During the green revolution, India became self-dependent for food production. The major outbreak of green revolution is deterioration of soil quality due to excessive use of agrochemicals to maximize crop yield. Nowadays, sustainability and health of soil are of great concern and that is why people are looking for alternatives of agrochemicals. Organic amendments and microbes are now being harnessed for their efficient use as biofertilizers and biopesticides. Liquid biofertilizers (LBF) can help improve soil quality, promote crop growth, and sustain soil health. Efficient soil microbes interact with plant roots where they get nutrition from root exudates and degrading organic matter. Although beneficial microbes possess ability to deal with various environmental issues, their application in well-organized way to resolve environmental problems is yet to be realized.

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Keywords

Application of biofertilizer · Food production · Sustainable agriculture

20.1 Introduction

Presently, the globally increase in human population raises a big threat to the food security of each people as the land for agriculture is limited and even getting reduced with time (Conway 2012). Therefore, it is essential that agricultural productivity should be enhanced within the next few decades to meet the large demand of future generation. With the expected rise in worldwide population, there is increasing environmental damage as a consequence of rapid growth in industrialization and urbanization (Glick 2012). Moreover, it is a significant challenge to feed the large population at present which inevitably will increase with time. Regardless, the enormous use of agrochemicals in agriculture makes the country self-dependent in providing large amount of food supply but simultaneously damages the soil health. After green revolution, over-reliance on agrochemicals for higher production inevitably damages both environmental ecology and human health. The exploitation of microbes as BFs is considered to some extent an alternative to agrochemicals in agricultural sector due to their extensive potentiality in sustainable food production. It has been reported that efficient microbes have showed BFs-like activities in the agricultural sector. Many reports on BFs have revealed their capability of providing required nutrients to the crop in sufficient amounts along with organic amendments that resulted in the enhancement of agricultural sustainability. In the present review, established facts observed and work carried out by many researchers on LBFs are discussed. This review also highlights about the potentialities of LBFs in different sectors including agriculture, ecology, and remediation that can craft LBFs as a promising tool for sustainable food production.

The indiscriminate uses of agrochemicals show great threat to nature by polluting air, water, and soil, these agrochemicals adversely affect soil in terms of depletion of water holding capacity, soil fertility, increased salinity, and disparity in soil nutrients (Savci 2012). Considering all the adverse effects of prolonged use of agrochemicals, microbes (BFs) have emerged as a potent alternative area in terms of the growing demand of healthy food supply, long-term sustainability, and concerns regarding environmental pollution (Reddy 2013). Although the use of agrochemicals is unavoidable to meet the rising demand of food in the world, there are opportunities along with organics.

20.2 The Concept of Liquid

The liquid biofertilizers (LBFs) are special liquid formulations of viable cells of beneficial microbes in an appropriate nutrient medium containing certain cell protectant chemicals. These chemicals not only promote cell survival during storage and after application to seed, but also provide protection to microbial cells under extreme conditions in soil such as high temperature and desiccation (Khandare et al. 2019). The LBFs are natural fertilizers which are microbial inoculants or in combination and they augment the availability of nutrients to the plants. The LBFs are suspensions having agriculturally useful microbes, which fix atmospheric nitrogen, solubilize insoluble nutrients, and make it available for the plants. The use of LBFs is eco-friendly and gives uniform results for most of the agricultural crops and directly reduces the use of chemical fertilizer by 15 to 40%. The shelf-life of the LBFs is higher compared to that of solid matrix base BFs. The LBFs are increasingly available in the market as one of the alternatives to chemical and organic fertilizers as well as solid substrate-based BFs. These beneficial microbes may enhance the growth of various crops and create healthy rhizosphere environmental conductions. The advantage of LBFs is that solid carrier is not needed. These products are also developed for potential application in modem agriculture such as soilless farming systems.

A LBF is a substance which contains living microbes which when applied to seeds, plants, or soil, colonizes the rhizosphere or the interior of the plants, and promotes plant growth by increasing the supply of nutrients to the host plant (Bardi and Malusa 2012; Malusa and Vassilev 2014). Nowadays, LBFs technology over conventional carrier based BFs shares more advantage and can be considered as a breakthrough in field of BFs technology and should find greater acceptance by farmers, extension workers, and commercial BFs manufactures. The LBFs are widely used to accelerate those microbial processes which augment the availability of nutrients that can be easily assimilated by the plants. They improve soil fertility by fixing the atmospheric nitrogen and solubilizing insoluble nutrients and produce plant growth-promoting substances in the soil (Mazid and Khan 2015). These LBFs have been promoted to harvest the naturally available biological system of nutrient mobilization which enormously increases soil fertility and ultimately, crop yield (Pandey and Singh 2012).

20.3 LBFs: Application

Imbalanced use of agrochemicals to meet the growing demand of food supply has undoubtedly led to contamination and severely damaged microbial habitats as well as beneficial insects. Nonetheless, the outcome of using excess chemical inputs has made the crops more prone to diseases and reduced soil fertility (Aktar et al. 2009). It is estimated that by 2020, to achieve the target production of 321 Mt. of food grain to feed 8 billion populations globally, the requirement of nutrients will be 28.8 Mt. while the availability will be only 21.6 Mt., creating a deficit of approximately 7.2 Mt. of required nutrients (Arun 2007). To feed the growing population with the deficit amount of available nutrients, the world certainly needs to flourish agricultural productivity and that too indeed in a sustainable and eco-friendly way (Pretty and Bharucha 2015).

Considering the hazardous effects of agrochemical, LBFs are supposed to be a safe alternative to agrochemical inputs and minimize ecological disturbance to a great extent. The LBFs are cost-effective, eco-friendly in nature and their prolonged use improves soil fertility substantially (Singh et al. 2011). It was reported that the use of BFs elevate crop yield 10-to-40% by increasing contents of proteins, essential amino acids, vitamins, and N-fixation (Bhardwaj et al. 2014). The benefits of using LBFs include cheap source of nutrients, excellent suppliers of microchemicals and micronutrients, suppliers of organic matter, secretion of growth hormones, and counteracting negative impact of agrochemicals (Gaur 2010). Uses of efficient microbes are vital components of soil and they play a crucial role in various biotic activities of the soil ecosystem which make the soil dynamic for nutrient mobilization and sustainable for crop production (Rana et al. 2012). Several reports (Table 20.1) have indicated that BFs alone or in combination with chemical fertilizers have great prospect in increasing productivity of many crops (Doifode and Nandkar 2014; Vijendrakumar et al. 2014; Shinde et al. 2018). The carrier based bioinoculants are currently being produced in the country and have been evaluated for their performance in different crops.

These inoculants suffer with major drawback of short shelf-life resulting in inconsistent performance under field conditions (Khandare et al. 2019). The fertilizer research is therefore focusing on shifting to the exploitation of microbes as a more eco-friendly approach for sustainable agriculture. The challenges to commercializing these kinds of LBFs are also discussed in Fig. 20.1.

1. The LBFs are eco-friendly bio-input being used to sustain the agriculture by reducing the agrochemicals inputs and improving the soil sustainability.

Quality is the major concern of BFs technology which often leads to poor performance in the field and thereby loses the farmers' faith.

The LBFs can improve plant growth through several different mechanisms as follows:

- Synthesis of plant nutrients or phytohormones, which can be absorbed by plants,
- Mobilization of soil compounds, making them available for the plant to be used as nutrients,
- Protection of plants under stressful conditions, thereby counteracting the negative impacts of stress, or
- Defense against plant pathogens, reducing plant diseases or death.

Recently, several efficient microbes have been used globally for many years as LBFs, contributing to increasing crop productivity and soil fertility which will in turn contribute to sustainable food production. The technologies for the production and application of microbial inoculum are under constant development and improvement. However, microbial-based LBFs market is growing steadily (Fig. 20.2). Nevertheless, the production and application of these products are heterogeneous among the different countries in the world.

Table 20.1 Effect of liquid biofertilizers (LBFs) on agricultural crops

Test plants	LBFs/chemical fertilizers	Response	References
Beta vulgaris L.	*Azotobacter* + PSB	Significantly maximum yield was recorded	Shinde et al. (2018)
Cicer arietinum	*Azotobacter* + PSB	Enhancement in seed germination, shoot length, and leaf chlorophyll contents were observed	Ansari et al. (2015)
Glycine max	*Bradyrhizobium* + PSB	Significantly increased growth and yield	Daravath and Takankhar (2018)
Ruta graveolens L.	*A. Lipoferum, P. striata, P. fluorescens*	Plant height, number of branches, number of compound leaves, stem girth and fresh biomass yield recorded highest compare to single inoculation	Vijendrakumar et al. (2014)
Solanum lycopersicum L.	*Ulva lactuca, Caulerpa sertularioides, Padina gymnospora, Sargassum liebmannii*	Significantly increase in germination parameters (percentage, index, meantime, energy, and seedling vigor index) and growth parameters (plumule length, radical length, shoot length, root length, fresh weight, and dry weight) of tomato seedlings	Hernández-Herrera et al. (2014)
Solanum lycopersicum "Roma"	*Acutodesmus dimorphus*	Seeds treated with *A. dimorphus* culture and with extract concentrations higher than 50% (0.75 g mL − 1) triggered faster seed germination-2 days earlier than the control group	Garcia-Gonzalez and Sommerfeld (2016)
Solanum melongena L.	*Stoechospermum marginatum*	Results exhibited that shoot and root length, total fresh and dry weight, leaf area were found to be enhanced in the leaves	Ramya et al. (2015)
	A. chroococcum, A. lipoferum, N levels	Significant improvement in yield attributes was recorded	Saiyad (2014)
	Azotobacter + PSB	Significantly enhances growth and yield	Doifode and Nandkar (2014)
Trigonella Foenum graecum L.	75% RDF + *Rhizobium* + PSB	All growth attributes, seed, and straw yield of fenugreek were recorded significantly higher	Kumawat et al. (2017)

(continued)

Table 20.1 (continued)

Test plants	LBFs/chemical fertilizers	Response	References
Triticum aestivum L.	*Azotobacter* + PSB	Significantly enhance growth, Yield, and nutrient uptake	Khandare et al. (2019)
	Trichoderma harzianum BHU51, varied N doses (100%, 75%, 50%, and 25% RDN)	Significantly enhanced nitrogen use efficiency (NUE), agronomic use efficiency (AUE), and physiological use efficiency (PUE)	Meena et al. (2016)
		Significantly higher leaf area, root infection, grain yield were recorded with combined application of *T. harzianum* with chemical N fertilization	Meena et al. (2017)
Vigna mungo L., *Zea mays* L.	*Azospirillum* + *Rhizobium* + *Azotobacter,* agrobacterium tumefaciens, rhizobium pusense, Flavobacterium anhuiense, rhizobium rosettiformans	Combined inoculation improves growth and yield	Maheswari and Elakkiya (2014)
		Application of chemical fertilizers along with *A. tumefaciens* strain OPVS10 showed pronounced beneficial effect on growth and yield attributes	Meena et al. (2018)
	Liquid biofertilizer-1 (LBF1) + carrier based culture (CB)	Improved yield attributes, grain, Stover, and biological yields	Gautam et al. (2017)
	Laurencia obtusa, Corallina elongate, Jania rubens	Application of *L. obtusa* + *J. rubens* plant height, K-content	Safinaz and Ragaa (2013)

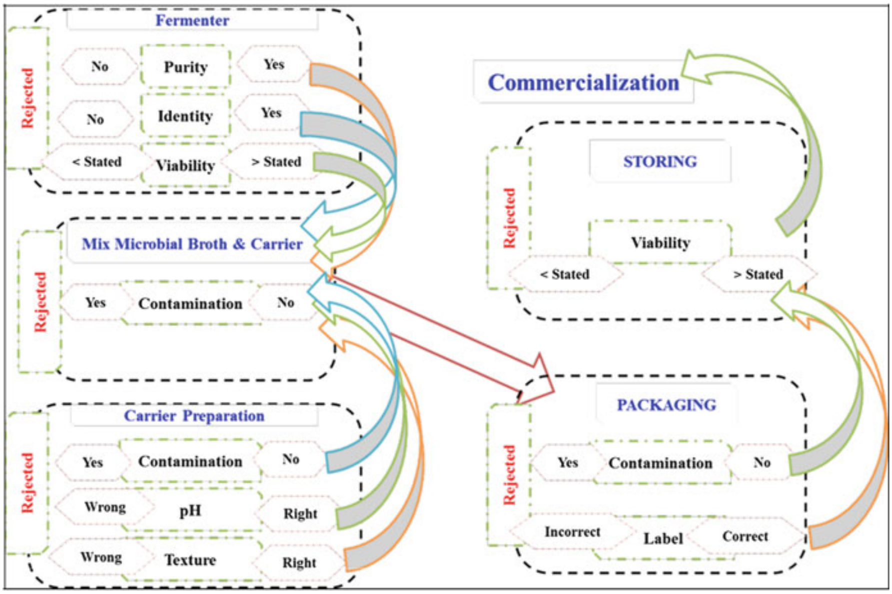

Fig. 20.1 Quality control in the liquid biofertilizers (LBFs) manufacturing process

20.4 Classification of LBFs

The LBFs are formulations of living beneficial microbes which may include one or more combinations of N-fixing, nutrient solubilizers, siderophore synthesizers, cyanobacteria, and mycorrhizal fungi. They can be classified based on the organisms, biological activity linked to BFs, and the symbiotic nature (Fig. 20.3). They can be found in rhizosphere or interior of the plant and contribute to its growth in many ways, either directly or indirectly, such as fixation of atmospheric nitrogen and making nitrogen available for plants, modulating the effects of environmental stresses (both biotic and abiotic), and regulation of plant growth and development of crops.

20.4.1 Methods of LBFs Application

Application of LBFs increases soil organic carbon, microbial biomass carbon, moisture retention capacity, and nitrogenase activity in roots or rhizosphere, thereby reinstating the agroecosystems which get exhausted and degraded due to agronomic practices associated with conventional farming (Seneviratne et al. 2011). Application details are described in Fig. 20.4.

Fig. 20.2 Necessity factors to augment liquid biofertilizers (LBFs) commercialization

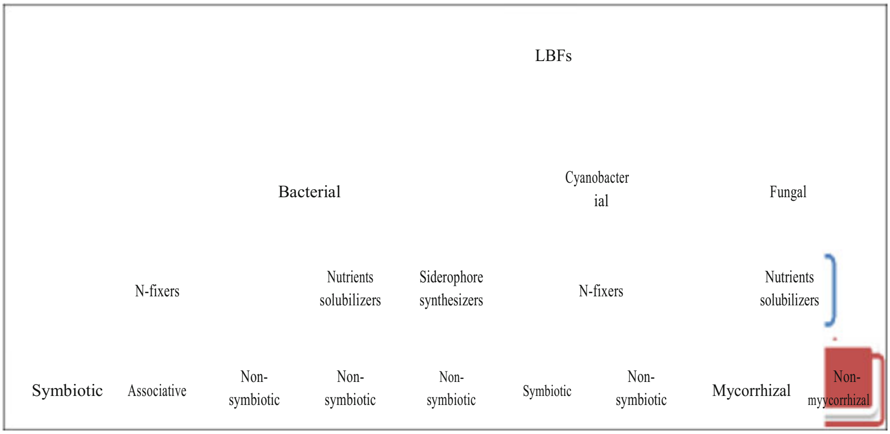

Fig. 20.3 Classification of liquid biofertilizers (LBFs)

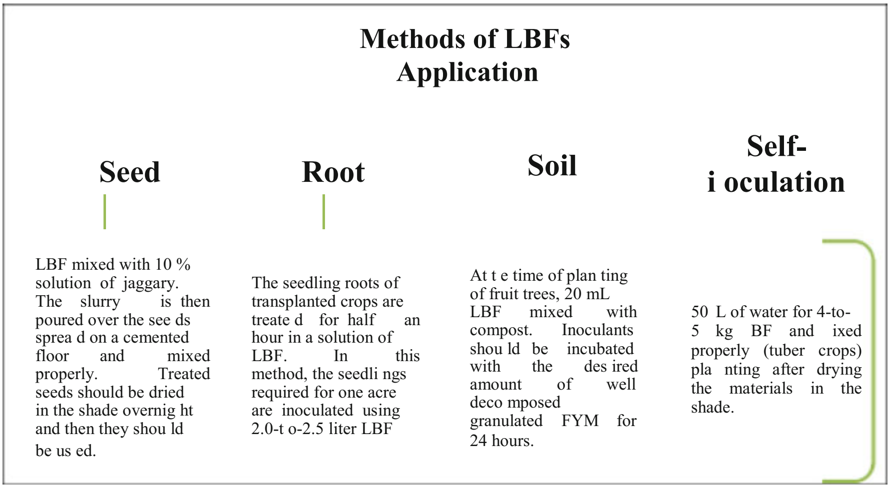

Fig. 20.4 Methods of liquid biofertilizers (LBFs) applications

20.5 Factors Affecting LBFs

The LBFs play an important role in improving soil sustainability. In addition, their application to soil improves the structure of the soil and minimizes the sole use of chemical fertilizers. Factor affecting the quality of LBFs is described in Fig. 20.5. The importances of LBFs are highlighted as secretion of plant growth hormones, improvement soil fertility, and reduction in the use of chemical fertilizers.

20.5.1 Advantages of LBFs

- LBFs have the potential to increase the soil health and productivity and also reduce the use of agrochemicals.
- LBFs are the diminished need to use other forms of fertilizer, many of which have some negative effects in the environment, if not properly utilized.
- The shelf-life of microbes in LBFs is quite high as compared to carrier based BFs.
- They are tolerant to high temperatures and ultraviolet radiations as compared to BFs.
- Special cell protectants or substances encourage formation of resting spores or cysts.
- Specialized nutrients ensure longer shelf-life, better survival on seeds as well as soil and tolerance to adverse conditions.
- Liquid formation is easy to handle and apply no loss of properties due to storage.
- Greater potentials to fight with native population. Dosages are 10 times lesser than BFs.

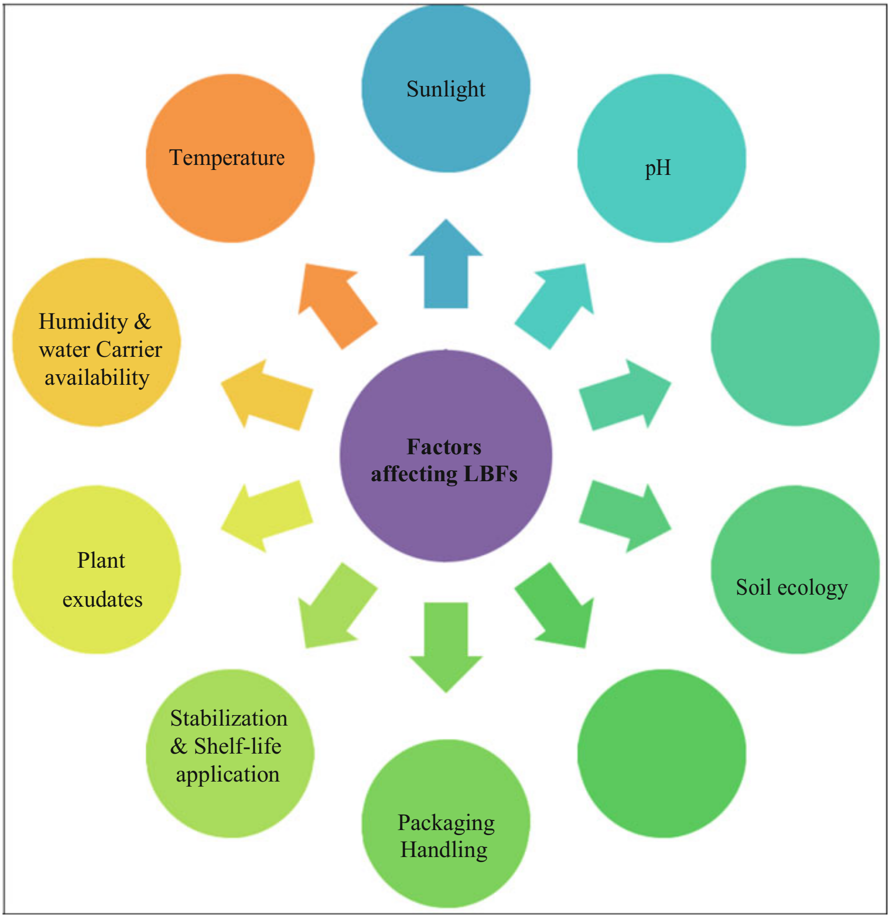

Fig. 20.5 Factors affecting liquid biofertilizers (LBFs) quality

- Very high enzymatic activity since contamination is nil and high commercial revenues.
- Easy to identification by typical fermented smell, an application of LBFs results in improved soil structure (porosity) and water holding capacity and enhances seed germination.
- They act as antagonists and suppress the incidence, as a bio-control, LBFs are cost-effective relative to agrochemicals.
- They can add 20-to-200 kg N/ha under optimum soil condition and thereby increase the crop yield (15–25%).
- LBFs enhance the plant growth-promoting activities, nutrients solubilizing (P, K, and Zn).
- They increase soil fertility and fertilizer use efficiency and ultimately the yield of crops.

20.5.2 Limitation of LBFs

The most important limitation of LBFs is their nutrient content when compared to inorganic fertilizers. This might result to deficiency symptoms in plants grown with the LBFs. However, this problem can be curbed by the addition of substances such as bone meal (rich in phosphorus), wood ash (rich in potassium), or other substances of natural origin such as phosphate rock to enrich the fertilizer. Also the use of nutrient rich wastes such as palm wastes (rich in potassium), wood ash (rich in potassium also) in making LBFs can help to remedy the problem.

20.5.3 Caution in the Use of LBFs

- Never mix LBFs with nitrogen fertilizers.
- Never apply LBFs with fungicides.
- Never expose LBFs to sunlight directly.
- LBFs are stored at room temperature (0 to 35 °C).
- Do not keep used solution overnight.

The biofertilizers market size by product (nitrogen-fixing, phosphate-solubilizing, potash-mobilizing), by application (seed treatment, soil treatment), by crop (cereals, pulses, oil seeds, fruits, vegetables), by form (dry, liquid), industry analysis report, regional details of market availability for LBFs in details is presented in Table 20.2.

20.6 Conclusion

In recent years, global food production facing greater challenges than ever before, due to decline in the productivity of agricultural crops in unprecedented rate. Over-reliance on agrochemicals for higher productivity not only hazardous for human health but also disturb the environmental ecology. LBFs have the capability of providing required nutrients to crops in sufficient amounts and help to meet the requirement of global food production to feed the increasing population. Therefore, it is very important to realize the significance and use of LBFs in modern agriculture. Although LBFs play a key role in enhancing the productivity of agricultural lands tremendously, the integrated approach to ascertain the most favorable plant–microbes interaction is the crucial factor that results the augmentation in productivity. Overall, advancement in the molecular biology not only helps in studying the most favorable plant–microbes interaction but also plays a vital role in optimizing the required protocols for LBFs. Despite the fact that the utilization of LBFs is blooming with great acceleration, still, it is essential to identify the potential strains of LBFs to explore the functioning of LBFs for their efficacy toward exploitation under sustainable agriculture.

Table 20.2 Various products of LBFs in markets with details

Names of companies	Product	Details information
Aaria bio-lifesciences research Pvt. ltd.-India	Biofertilizer, seaweed extract, soil conditioner, plant growth promoters	http://www.aariabiolife.com
Anu biotech international-India	Biofertilizers for agricultural use	http://www.biotech-int.com
Bhaskar agrochemicals ltd.-India	Coated granules, granules, soluble granules	http://www.bhaskaragro.com
Bio organic industries-India	Biopesticide and biofertilizers	http://bioorganic.co.in
Gujarat life sciences (p) ltd-India	Nitrogenous urea, biofertilizer, urea, ammonia	http://www.glsbiotech.com
Hindustan organic chemicals ltd.- India	Aniline, formaldehyde, nitrobenzene, ortho- nitro-toluene	http://www.hoclindia.com
Indore Biotech Inputs & Research (p) ltd.- India	Bio-control agent, biofungicides, biopesticides	http://www.indobioagri.in
Karnataka agro chemicals multiplex fertilizers Pvt. ltd.-India	Micronutrients, pesticide goods, biofertilizer, biopesticides	https://www.multiplexgroup.com
Krishak Bharati cooperative limited-India	Nitrogenous urea, biofertilizer, ammonia	https://www.kribhco.net
Lotus biotech- India	Biofertilizers, biopesticides, biofungicides	https://lotus-biotech.business.site
Madras fertilizers ltd.-India biofertilizers	Biofertilizers	http://madrasfert.co.in
MD biocoals Pvt. ltd.- India	Organic manure, organic fertilizer, liquid organic fertilizer	http://www.mdbiocoals.com
Migrow agro products- India	Bio organic products, biofertilizers	http://migrowindia.com
Molecraft life sciences- India	Biofertilizers, biopesticides	http://www.molecraft.com
Mount natural fertilizer ltd.-India	Biofertilizer, mount natural fertilizer	http://www.mountnaturalfertilizer.com
Nagarjuna agro chemicals Pvt. ltd-India	Biofertilizers, biopesticides	https://www.nagarjunaagrochemicals.com
Neesa Agritech & Foods ltd.-India	Biofertilizers, biopesticides	http://www.neesaagritech.com
Prabhat fertilizer & chemical works-India	Manufacturers of biofertilizers, zinc sulfate	https://www.prabhatagri.com
Shivam bio and plantation-India	Organic fertilizers, biofertilizers	http://www.shivambioandplantation.in
Vision mark biotech-India	Biofertilizers, organic fertilizers, biopesticides	http://www.visionmarkbiotech.in

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21 Employment of Seed Priming as a Salt-Stress Mitigating Approach in Agriculture: Challenges and Opportunities

Abdul Majeed, Zahir Muhammad, and Saira Siyyar

Abstract

Salinity is one of the several abiotic constraints which prevail under natural and managed ecosystems. The stress drastically affects seed establishment, physiology, and developmental aspects of plants, which are often associated with low yields of economically important crops. To minimize the adverse effects of salt stress on crops, employment of sustainable and cost-effective methods is extensively desired. Seed priming, a technique of pre-germination mediation of seeds which can lead to their ample responses to stresses, has a promising role in the adaptability of plants to salinity stress. Preconditioning with water and several other osmolytes, heat, and irradiation can lead to improved metabolism and post-germination responses of seed when they are encountered by salinity. Selection of appropriate priming agents, understanding of the underlying mechanisms, and economic costs are the leading factors which can lead to the wide adaptability of seed priming in agriculture as a salt-stress mitigating method. The focus of this chapter is to discuss the potential application of different priming methods for reducing the adverse effects of salinity and challenges in agriculture.

Keywords

Osmopriming · Irradiation · Ionic toxicity · Salinity stress · Antioxidative system · Reactive oxygen species

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21.1 Introduction

Plants are exposed to a diverse range of abiotic and biotic stresses which often result in their altered growth, development, and productivity (Jisha et al. 2013). Among the stresses, salinity remains leading abiotic restraints which hamper germination, growth, and many metabolic and physiological activities of plants (Shrivastava and Kumar 2015; Negrão et al. 2017). More than 800 million hectares of land throughout the world is estimated to be salt-affected (Munns and Tester 2008). The problem poses threats at an alarming level in arid and semi-arid regions which are characterized by low rainfall and high evapotranspiration rates (Munns and Gilliham 2015; Elgallal et al. 2016). Different plants respond differentially to salinity; however, nearly all plants to some extent are sensitive to salt stress and generally exhibit a frail performance in germination, growth, physiology, and overall development. Salt-triggered adversities on plants are linked with water deficit conditions in soils and ionic toxicity inside tissues, the production of reactive oxygen species, oxidative damage of enzymes and other molecules, retarded leaf growth, increased senescence, abnormal photosynthesis, and respiration which would lead to reduced growth and yield of stressed plants (Ahmad et al. 2018; Wu et al. 2018). Although in a natural ecosystem, plants respond to the imposed stresses by different adapted mechanisms (Wang et al. 2003); in managed ecosystem, however, cultivated crops are more prone to the salt adversities because of domestication outcomes and agricultural intensification. Thus sustainable and cost-efficient efforts to make plants adapted to salinity stress are certainly necessary.

During the last few years, major emphasis has been given to the development of salt-tolerant genotypes of crops by using classical and biotech breeding in addition to the utilization of exogenous application of hormones, microbes, and arbuscular mycorrhizal fungi (Farooq et al. 2015), costs, technical difficulties, and labor associated with those methods may not efficiently work to reduce salinity imposed stress in cultivated crops. Seed priming—a condition in which seeds are pre-treated with different agents—seems an ideal and low-cost method to induce salt tolerance in plants (Kubala et al. 2015; Majeed et al. 2018). Seed priming acts through several mechanisms which include modification in cell membranes, imbibition, and dormancy, the activation of the antioxidative system, regulation of biomolecules, and metabolic activities of the germinating seeds (Ibrahim 2016; Hussain et al. 2016a, 2016b; Majeed et al. 2018). In several studies, different priming techniques have been shown to improve the germination, seedling emergence, growth, water uptake, and photosynthetic activity in sunflower, Lucerne, maize, wheat, rice, and other crops under high salt concentrations (Kaya et al. 2006; Zhang et al. 2007; Anosheh et al. 2011; Bakht et al. 2011; Jafar et al. 2012). Knowledge about the suitable priming agents, economic costs, and response of the pre-treated crops to salinity stress is an important driver in opting for seed priming as a salinity management technique. This chapter summarizes the role of different priming techniques in inducing stress tolerance to different crops under salinity.

21.2 Responses of Crop Plants to Salinity Stress

Soil salinity has several adversities on cultivated crops. It affects germination, growth, physiology, biochemistry, and subsequent yield outputs of crops in a negative manner although different crops have different tolerance potentials to the salinity stress (Munns and Tester 2008; Parihar et al. 2015). Salinity primarily affects crops by producing osmotic stress which hinders germination and seedling establishment, although this phase of stress is tolerated to some extent in most of the crops (Munns and Tester 2008). The second phase of salinity which has more drastic effects on crops is the "ionic stress" where an elevated level of ions accumulates in plant tissue causing ionic toxicity and which consequently lead to reduced leaf area, and plant growth (Läuchli and Grattan 2007). When crops are grown under saline conditions, they are challenged with osmotic stress due to water deficiency and ionic stress due to the accumulation of higher Na and Cl ions in shoots (Tavakkoli et al. 2010). Higher accumulation of ions in tissues corresponds to the toxic environment inside cells thereby affecting enzymes and their functions, vital metabolites, and general metabolic activities.

Seed germination is the initial phase towards successful plant establishment and during this phase, most of the metabolic events and mobilization of the stored substances occur which are arrested as a result of salinity stress (Bewley et al. 2012; Kubala et al. 2015). Effect of salinity on altered germination patterns of crops may be either due to osmotic stress which prevent the sufficient absorption of water by seed coat or it may be due to the toxicity posed by salt ions (Na and Cl) for the germinating seeds (Khajeh-Hosseini et al. 2003; Janmohammadi et al. 2008). Singh et al. (2012) have noted an increased duration for germination completion and reduced germination rate in tomato when the crop was challenged with 4.5 dSm^{-1} NaCl solution. In other studies, reduced germination, seedling vigor, and delay in germination time in response to salinity for common bean (Cokkizgin 2012), sorghum (El Naim et al. 2012), sesame (Bahrami and Razmjoo 2012), maize (Khodarahmpour et al. 2012), wheat (Hussain et al. 2013), pea (Tsegay and Gebreslassie 2014), rice (Vibhuti et al. 2015), and pulses (Awasthi et al. 2016) have been recorded. For normal germination of seeds, the appropriate amount of water and its absorption is essential. Similarly, synthesis of new molecules, gene expression, and timely breakdown of the respiratory substrates, enzymatic and hormonal communication are prerequisites for germination success. Salinity stress disturbs these processes which consequently lead to abnormal germination activities which become evident in the form of low germination percentage, germination index, and delay in mean germination time.

Seedling and subsequent shoot growth and development depend on several factors among which absorption of water, mineral, pH of the soil and cellular environment, proper synthesis of photosynthate, energy production, secondary metabolism, and activation of stress hormones are important ones (Rengasamy 2010; Akula and Ravishankar 2011). Under saline conditions, general growth retardation of crops is widely observed which may be attributed to the accumulation of Na and Cl ions in shoots and leaves, the ionic toxicity, production of reactive oxygen species, changes in pH, suppression in enzymes and hormones, fluctuation in opening and closures of stomata, and lower rate of photosynthesis (Wu et al. 2010; Amirjani 2011; Qados 2011; Parihar et al. 2015). Previously drastic effect of salinity on shoot growth, accumulation of Na ions, reduced photosynthetic pigments and proteins, and some physicochemical attributes in rice (Jamil et al. 2012; Hakim et al. 2014; Ologundudu et al. 2014), tomato (Haghighi and Pessarakli 2013), mung bean (Ahmad et al. 2012), cucumber (Kang et al. 2014), maize (Rojas-Tapias et al. 2012), potato (Jaarsma et al. 2013), chickpea (Rasool et al. 2013), okra (Dkhil and Denden 2012), and wheat (Yasmeen et al. 2013) have been well established.

Finally, yield and production of crops are determined by adequate photosynthetic activity in leaves which require roots to absorb sufficient amount of water and active stomatal functioning for allowing the entry of CO_2. Salinity stress particularly that of NaCl may influence the integrity of cell membrane through Na–K exchange, thus allowing more sodium to enter through roots (Chartzoulakis 2005). Replacement of K^+ with Na^+ may correspond to abnormalities in stomatal opening and closing, osmotic balance inside the plant, and several enzymes since K+ is an active driver of such processes and in the regulation of enzymes particularly pyruvate kinase (Mahajan and Tuteja 2005). An increased sodium entry to plant may further trigger Cl uptake which gives rise to the accumulation of Na^+ and Cl^- in leaf tissues. This would create a toxic environment for photosynthetic enzymes to function properly and to generate maximum photosynthate thereby reducing the final yield output of crops. Chaves et al. (2009) argued that salinity stress either directly or indirectly results in photosynthetic abnormalities which can cause lower growth and yield. In earlier work, reduced growth, photosynthesis, and yield in rice (Ali et al. 2004; Shereen et al. 2005), mung bean (Ahmed 2009), squash (El-Mageed et al. 2016), maize (Feng et al. 2017), and tomato (Ahmed et al. 2017) due to salinity stress have been demonstrated.

21.3 Seed Priming Techniques and Influences on Crops Under Salinity Stress

Seed priming or preconditioning is an important physiological approach which aims at preparing seeds to respond properly to the stressful environment after they are sown (Anosheh et al. 2011; Sano et al. 2017). The technique employs pre-exposure of seeds to either chemical compounds or physical treatments for a specific duration (Paparella et al. 2015; Song et al. 2017). The exposure to chemical or physical stress induces changes in several physical and biochemical attributes of seeds prior to germination which is expected to exhibit better performance in normal as well as in stressed conditions. Different priming agents have been used in agriculture which have contributions to improved germination, growth, physiological and yield performance of major field crops under salt stress.

Seeds are generally primed with water (hydropriming), salts (halopriming), osmolytes (osmopriming), biological agents (biopriming), and solid matrix (Ashraf and Foolad 2005). Hydropriming is one of the efficient and cost-effective priming methods which involve seed treatment with water for a specific period which alters the imbibition potentials, synthesis of new molecules at different stages, and the preparation of radical emergence in pre-treated seeds (Varier et al. 2010; Parera and Cantliffe 1994). Water soaked seeds are dried after treatment and their initial dry weight is achieved before sowing (Ashraf et al. 2018). The process may be carried out either in aerated condition (aerated hydropriming) or under anaerobic conditions. Moreover, the seeds may be soaked completely in water or they may be partially moistened. The provision of aerated or non-aerated conditions and partial or complete hydration of seeds depends on plant species and the advantages and disadvantages linked with respective methods (Parera and Cantliffe 1994; Ashraf and Foolad 2005). Kaya et al. (2006) achieved better seed germination and root and shoot growth in sunflower when seeds were primed with water and subsequently exposed to NaCl stress at 6.5–23.5 dSm/1. Amooaghaie (2011) demonstrated the efficacy of hydropriming in improving germination potentials, and root and shoot growth in alfalfa at 150 Mm NaCl stress. Moghanibashi et al. (2012) documented that hydropriming for 24 hours induced salinity tolerance to sunflower and resulted in its improved germination, growth, and dry mass in salinity imposed stress. Dai et al. (2017) outlined that hydropriming and pretreatment of soybean seeds with some other priming agents significantly improved growth and biochemical activity of the tested plant which was exposed to soda saline-alkali stress (10 Mm l^{-1}). Sunflower seeds treated with water exhibited enhanced germination, shoot and root growth, and dry weight under 16 dSm/1 salinity stress which was significantly higher than unprimed seeds (Matias et al. 2018).

Another widely practiced technique is halopriming which employs seed treatment with a known concentration of inorganic salts (Ashraf and Foolad 2005). For halopriming, differential concentrations of sodium chloride (NaCl), calcium chloride ($CaCl_2$), copper sulfates ($CuSO_4$), zinc sulfate ($ZnSo_4$), potassium nitrate (KNO_3), etc., are used to induce priming-properties in treated seeds (Jisha and Puthur 2014; Gholami et al. 2015). Studies demonstrate that $CaCl_2$, NaCl, KNO_3, and KCl priming brought improvement in germination, seedling growth, biomass and yield, and antioxidative activities of wheat (Iqbal and Ashraf 2007; Islam et al. 2015), tomato (Nawaz et al. 2011), hot pepper (Amjad et al. 2007; Khan et al. 2009), rice (Afzal et al. 2012), sugarcane (Patade et al. 2009), lentil (Ghassemi-Golezani et al. 2008a, 2008b), black seed (Gholami et al. 2015), Indian mustard (Srivastava et al. 2010), and chickpea (Ali and Kamel 2009) which were grown under different concentrations of NaCl.

In addition to inorganic salts, organic osmolytes such as polyethylene glycol (PEG), mannitol, glycerols, salicylic acid, ascorbic acid, growth hormones, natural plant extracts (seaweed extracts, sorghum extracts, moringa leaf extracts), and pesticides have been used as priming agents (Sivritepe 2008; Ziosi et al. 2012; Paparella et al. 2015; Kalaivani et al. 2016; Wojtyla et al. 2016; Bajwa et al. 2018). Different osmotica used as priming agents have different roles in the osmotic modification of treated seeds and hence differential efficiencies in modulating the behavior of seeds under the stressed environment (Parera and Cantliffe 1994; Kaur et al. 2002). Since the osmopriming adds only a specific amount of water to seeds for a specific duration, seeds are not allowed to emerge radicle because of partial hydration (Wojtyla et al. 2016). Priming with selenium and silicon (Khaliq et al. 2015; Abdel Latef and Tran 2016; Moulick et al. 2016), H2O2 (Wahid et al. 2007; Hameed and Iqbal 2014; Azimian and Roshandel 2016), solid matrices (Paparella et al. 2015; Sen and Mandal 2018), and biological agents (Kaymak et al. 2009; Jisha and Puthur 2016; Pehlivan et al. 2017; Chatterjee et al. 2018) have been proven techniques in conferring salinity and other abiotic stress tolerance to a variety of crops. A list of commonly used priming agents which are used as salt-mitigating approaches for different crops is presented in Table 21.1.

21.4 Mechanism of Priming-Induced Salinity Tolerance in Crops

The technique of seed priming provokes several physiological and metabolic alterations in pre-treated seeds which correspond to a better performance once they are challenged with salinity stress (Fig. 21.1). There are many mechanisms involved in stress tolerance activation of seeds. Foremost, partial hydration of seeds results in a changed membrane permeability which allows the seeds to take up water and nutrient at a faster rate thus enabling germination to proceed abruptly (Wojtyla et al. 2016). Priming may modulate the respiratory events, which are crucial for germination, in seeds before germination as a result of imbibition with plenty of energy in hand for the synthesis of necessary biomolecules (Paparella et al. 2015; Płażek et al. 2018). Earlier studies reported that osmopriming improved respiration of sorghum and rice under chilling stress (Patane et al. 2006; Hussain et al. 2016a, 2016b; Wang et al. 2016) suggesting the same could potentially contribute to improved respiratory events and better germination under saline conditions. Pre-germination metabolic activities in primed seeds are boosted which generally impart healthy influences on seed germination and vigor (Wang et al. 2016). The action of enzymes concerned with metabolic processes which are necessary for the emergence of radicle and plumule is generally enhanced during the priming processes resulting in improved growth of seedling (Kaur et al. 2006). Stimulatory effects of hydropriming, halopriming, and osmopriming on stress regulatory enzymes such as catalase, superoxide dismutase, and peroxidase and general antioxidative activities have been observed in different seeds encountered by salinity and other stresses (Salah et al. 2015; Islam et al. 2015; Nasibi et al. 2016; Sheteiwy et al. 2016). Improvement of the antioxidative system leads to better management of reactive oxygen species generated during salinity stress by the primed plants (Chen and Arora 2011). An interesting illustration of seed priming-induced stress tolerance in plants is the potential familiarization of seeds with "stress memory" which they gain when exposed to priming-stress before the actual stress (Bruce et al. 2007). Hilker et al. (2016) outlined that pre-exposure of plants, fungi, and bacteria to direct abiotic stresses or future stress indicators can make them "primed" against such stresses and the priming mechanism could be analogous to acquired resistance (in animals) which operate through several cellular, epigenetic, hormonal, and molecules signaling modifications.

Table 21.1 Role of different priming agents in salinity mitigation of some crops

Plants	Priming agents	Salinity stress	Response	Reference
Zea mays L. (maize)	Water, NaCl, KCl, $CaCl_2$	NaCl; 200 mM	Improved germination	Ashraf and Rauf (2001)
Helianthus annuus (sunflower)	Water, KNO3	6.5–23.5 dSm^{-1}	Increased germination and seedling lengths	Kaya et al. (2006)
Medicago sativa (lucerne)	Brassinolide	13.6 dSm^{-1}	Improved growth, fresh and dry biomass, and anti-oxidant enzymes	Zhang et al. (2007)
Brassica juncea L. (Indian mustard)	Water	NaCl; 150 mM	Improved dry biomass and total chlorophyll content	Srivastava et al. (2010)
Triticum aestivum L. (wheat)	NaCl	NaCl: 120 mM	Growth and biochemical attributes improved	Jamal et al. (2011)
Hordeum vulgare (barley)	NaCl	NaCl; 150 mM	Improved growth and biomass	Anwar et al. (2011)
Vigna radiata (mung bean)	Salicylic acid	NaCl; 270 mM	Enhanced germination	Entesari et al. (2012)
Zea mays (maize)	NaCl	NaCl; 8 g/L	Improvement in early growth	Abraha and Yohannes (2013)
Vicia faba (broad bean)	Nicotine and ascorbic acid	NaCl: 150 mM	Improvement in physicochemical events	Azooz et al. (2013)
Solanum tuberosum (potato)	24-epibrassinolide	NaCl; 30 mM	Enhanced growth and biochemical characters	Khalid and Aftab (2016)
Oryza sativa L. (rice)	NaCl and 2,4-dichlorophenoxyacetic acid	NaCl; 4-8dSm/1	Combined treatment with NaCl and 2,4-D improved root growth and biomass, reduced Na and K uptake	Islam et al. (2017)
Glycine max (soybean)	Water, $CaCl_2$, GA3, NaCl, $ZnSO_4$	NaHCO3 and Na2CO3	Improved growth and physicochemical characters	Dai et al. (2017)

(continued)

Table 21.1 (continued)

Plants	Priming agents	Salinity stress	Response	Reference
Chenopodium quinoa (quinoa)	Saponin	NaCl; 400 mM	Improved growth and yield	Yang et al. (2018)
T. aestivum (wheat)	Sodium nitroprusside	NaCl	Grain yield and biomass enhanced	Ali et al. (2017)
Solanum lycopersicon (tomato)	Calcium and 24-epibrassinolide	NaCl; 150 mM	Reduced Na and Cl uptake, regulation of oxidative stress	Ahmad et al. (2018)
Z. mays (maize)	$ZnSO_4$	NaCl; 100 mM	Better growth, mineral uptake, biomass	Imran et al. (2018)
T. aestivum (wheat)	Aspirin	NaCl; 10 dSm^{-1}	Improved and vigorous growth	Hussain et al. (2018)

Since salinity stress is often associated with the production of ROS (Chaves et al. 2009), the ROS can cause DNA damage, lipid peroxidation, protein and carbohydrates degradation, and membrane instability which may attribute to retarded germination and general growth activities of plants (Savvides et al. 2016; Wojtyla et al. 2016). Priming is better known to repair damaged DNA, while potentially involved in synthesizing new DNA, RNA, proteins, and enzymes (Varier et al. 2010; Pagano et al. 2017). The role of priming in DNA repair in chickpea (Sharma and Maheshwari 2015), sugar, and proline synthesis in maize (Karalija and Selović 2018), protein synthesis and transcription in rapeseed (Kubala et al. 2015), regulated transcription in rice (Hussain et al. 2016a, 2016b; Samota et al. 2017) after exposure to salinity or drought stress has been reported. Regulation of growth and stress hormones in response to priming is likely to be linked with priming. Auxins, abscisic acid (ABA), ethylene, gibberellins (GAs), and Jasmonic acid are known to play crucial roles in adapting plants responses to salinity stress (Zhang et al. 2006; Ryu and Cho 2015) and priming treatments might potentially enhance the activities of these hormones thus providing plants vigor under salt stress (Majeed et al. 2018). Iqbal et al. (2006) documented enhanced concentration of ABA and auxin in wheat in salinity imposed conditions as a result of halopriming with NaCl, KCl, and $CaCl_2$. Moreover, many of the priming agents are regarded as “signaling molecules” which trigger defense responses in different plants towards biological and environmental stresses (Dong et al. 2014; Li et al. 2017). It has also been noted that appropriate mobilization and degradation of stored substances in seeds triggered by priming at the time of stress would lead to concurrent amelioration of the consequences posed by that stress (Ella et al. 2011).

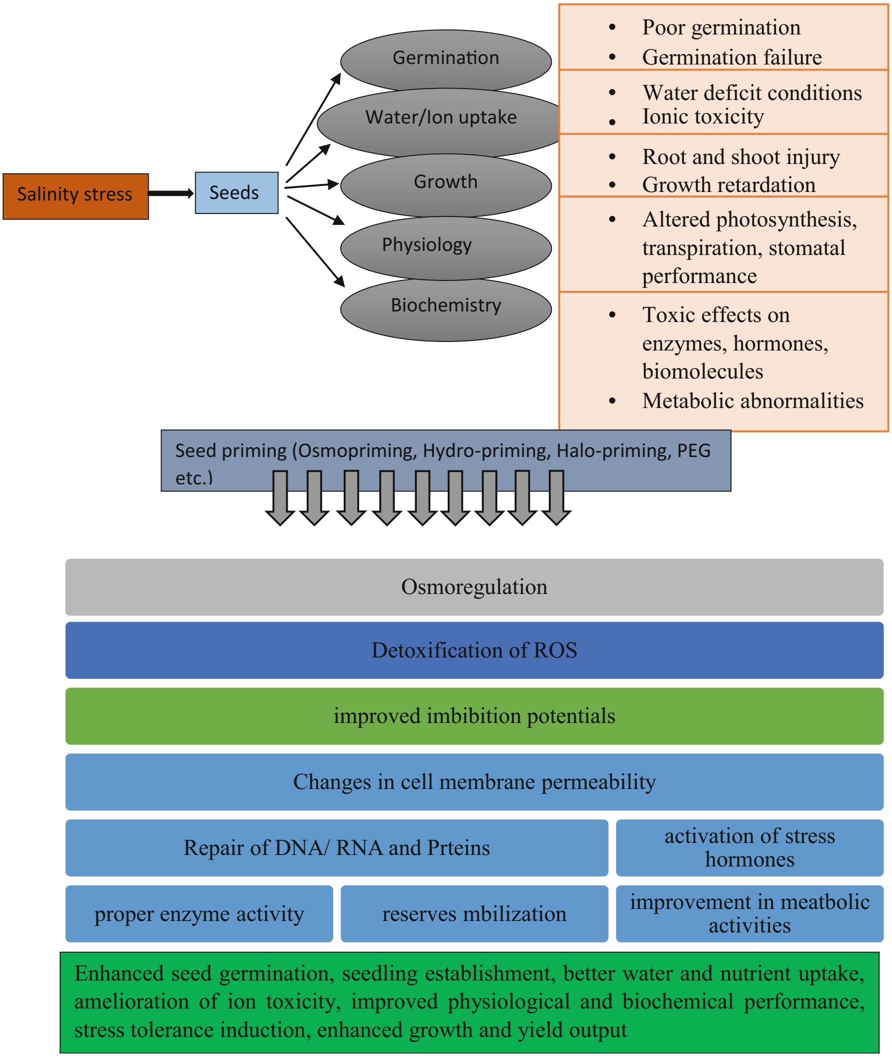

Fig. 21.1 An illustration of the adverse effects of salinity on seeds and role of seed priming in mitigation of salinity stress; PEG, polyethylene glycol; ROS, reactive oxygen species

21.5 Employment of Seed Priming: Challenges and Opportunities

Relevant studies on seed priming suggest that priming techniques have great potentials in agriculture for mitigating the adverse effect of salinity on germination, physiological and biochemical attributes, and growth and yield of field crops (Harris et al. 2001; Paparella et al. 2015). Yet there are several challenges which reduce the wide application of seed priming in agriculture for stress management of crops in the field. Sano et al. (2017) highlighted that primed seeds show vulnerability to deterioration and hence their longevity is lost which remain a key hurdle in the commercial success of priming applications. In many studies reduced germination of primed seeds of different crops has been observed when they were stored for different periods as a result of reduced seed longevity (Chiu et al. 2002; Schwember and Bradford 2005; Hussain et al. 2015; Wang et al. 2018) which indicates the reversal of the benefits which were attained during the priming process. Deterioration in seed quality and reduced storage life of primed seeds are considered to be due to limited antioxidation and peroxidation, metabolism of stored reserves, and the accumulation of specific substances in seeds which impart negative effects on seed longevity (Chiu et al. 2002; Wang et al. 2018). Moreover, non-uniformity in hydration capacity and subsequent germination, non-suitability of some seeds to hydropriming (Ashraf and Foolad 2005), and toxic effects of some salts on seeds due to the accumulation of salts (Bradford 1995) are some hindering factors in the wide adoption of seed priming as stress management approaches. Non-screening for good quality seeds during priming processes makes the technique insufficient (Bruggink 2004). Incurring of economic costs in case of some priming agents and non-feasibility of the general procedures at farm level are also among the constraints which highlight the drawbacks of seed priming.

Besides potential drawbacks of some of the priming methods and inappropriateness of some crops species for subjecting them to seed priming, the process of priming has general acceptance in agriculture and yields better responses in terms of germination, stand establishment, and final yield of major field crops (Paparella et al. 2015; Bose et al. 2018). Hydropriming and halopriming particularly with NaCl offer cost-effective strategies to induce salt tolerance in many agricultural crops. Since unequal water absorption remains a leading problem with hydropriming, determination of the appropriate amount of water for priming, soaking duration, and consequent dehydration could improve these adversities (Majeed et al. 2018). Similarly, salt accumulation with halopriming may be handled with dipping in water following drying to the initial dry weight of seeds. Challenges with the longevity of seeds may be dealt with molecular and proteomic approaches. Harris (2006) suggested that "on farm" seed priming where farmers use overnight priming of seeds with water before sowing them is a practical approach which is cost effective, environmentally friendly and imparts beneficial influences on the yield of crops. Tanou et al. (2012) advocated extensive studies on proteomic approaches targeting the stress mitigating proteins and signal pathways which may play a significant role in the success of priming techniques. Sano and Seo (2019) proposed that more comprehensive research on cell cycle inhibitors might help in reducing the adverse side effects of seed priming on seed longevity.

21.6 Conclusions

Salinity, a devastating problem in agriculture, is known to cause abnormal germination patterns, crop establishment, and significantly lower yields in field crops because of associated osmotic stress and ionic toxicity. The problem is widespread and needs much scientific attention for developing sustainable strategies to suppress its adverse effects on crops' yields. Genomic and molecular tools are ideal approaches to develop salt-tolerant cultivars; these techniques, however, still require greater efforts, expertize, and costs besides fewer success ratios. Seed priming instead serves as an easy to perform, a less costly and eco-friendly method for introducing the seeds with prior exposure to stress. Hydropriming, halopriming, and priming with an osmotic solution can enhance seed germination, seedling growth, and plant yield under salinity stress. Basic mechanisms involved in priming-induced tolerance in crops to salinity include mobilization of stored reserves, activation of several enzymes and hormones, repairing DNA, RNA, and synthesizing new molecules which may serve as stress mitigating factors. For handling the problems related to shelf life more extensive studies are needed covering molecular and proteomic aspects.

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Microbial Approaches for Bio-Amelioration and Management of Salt Affected Soils

22

Sanjay Arora

Abstract

The salt affected soils that include saline and alkali soils are poor in organic carbon content and therefore the microbial activity and ultimately plant growth is significantly affected. Halophilic microbes are the organisms that are tolerant to salt stress. In recent past, several species of halophiles have been isolated and reported from different saline environments from various parts of the world. The mechanism of halophiles to tolerate salt stress is mainly by expressing aminocyclopropane-1-carboxylic acid (ACC) deaminase activity that removes stress, ethylene from the rhizosphere and some halophiles produce auxins that promote root growth. Halophilic plant growth promoting bacteria that live in association with plant roots alleviate salt stress for better growth and yield, through their own mechanisms for osmotolerance, osmolyte accumulation, asymbiotic nitrogen fixation, solubilization and mineralization of essential plant nutrients and production of plant growth hormones. Plant growth promoting halophilic bacteria induce plants salt stress tolerance and can help in coming out with the cost-effective solution for saline soils, improving agricultural crop yields and improving soil health. Inoculation of halophilic plant growth promoting bacteria through their formulations is known to mitigate salt stress and enhances crop growth and yields. In this chapter, the use of halophilic plant growth promoting microbial inoculants for bio-remediation of salt affected soils, crop growth enhancement and their impact on soil biochemical properties as well as their role in recent advancement for the rehabilitation of degraded lands is discussed in detail.

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Bio-remediation · Halophiles · PGPR · Salt tolerance · Salt affected soil

22.1 Introduction

Agricultural salinity is a major environmental constraint affecting crop production. The soil that contains excess salts impairs its productivity. A build-up of salts in the soil may influence its behaviour for crop production through changes in the proportions of exchangeable cations, soil reaction, physical properties and the effects of osmotic and specific ion toxicity. The salt affected soils in India are broadly placed into two categories: (1) alkali or sodic soils and (2) saline soils. The sodic or alkali soils in general are characterized by high soil pH (up to 10.8), high exchangeable sodium per cent (ESP) up to 90, low organic carbon, poor infiltration and poor fertility status. These soils are dominated by sodium carbonate and sodium bi-carbonate salts. Presence of excess amount of Na makes the soils deflocculated resulting in poor physical condition. Conversely, the saline soils have higher electrical conductivity (> 4dS/m), low ESP (< 15%) and low pH (< 8.5). The dominant salts in saline soils include chlorides and sulphates of Na, Ca and Mg. Most of these salts are soluble in nature and can be leached out from the soil profile, if sufficient quantity of water is available for leaching.

In present situation where irrigated agriculture has attained optimum yield levels there is scope to harness the marginal salt affected soils to enhance crop production to feed the burgeoning population of the country. The state wise extent of salt affected soils in India is given in Table 22.1. Out of the total 6.727 million ha of salt affected soils, 2.956 million ha are saline and the rest 3.771 million ha are sodic. Out of the total 2.347 million ha salt affected soils in the Indo-Gangetic Plains, 0.56 million ha are saline and 1.787 million ha are sodic. Also there are reports of emerging salt affected soils from Jammu and Kashmir, mainly due to excessive use of irrigation water, chemicals and/or canal seepage (Sharma et al. 2012; Gupta and Arora 2016).

22.2 Reclamation and Management of Salt Affected Soils

Sodic soils are generally reclaimed using gypsum along with organic amendments/ manures. The availability of mineral gypsum and also manures is scarce these days. Also the estimation of gypsum requirement of sodic soil is tedious and most of the soil testing laboratories either do not have facility for gypsum requirement or lack expertise in estimation, so a model was developed to estimate gypsum requirements based on soil pH value. The mobile application 'GypCal' in English and Hindi was developed to promote judicious use of chemical amendment gypsum for reclamation of sodic soil using soil pH as input and this application is made freely available for download through Google Play Store (Fig. 22.1).

Table 22.1 Extent of salt affected soils in India (ha)

State	Saline	Sodic	Total
Andhra Pradesh	77,598	196,609	274,207
Andaman and Nicobar Island	77,000	0	77,000
Bihar	47,301	105,852	153,153
Gujarat	1,680,570	541,430	2,222,000
Haryana	49,157	183,399	232,556
Karnataka	1893	148,136	150,029
Kerala	20,000	0	20,000
Madhya Pradesh	0	139,720	139,720
Maharashtra	184,089	422,670	606,759
Orissa	147,138	0	147,138
Punjab	0	151,717	151,717
Rajasthan	195,571	179,371	374,942
Tamil Nadu	13,231	354,784	368,015
Uttar Pradesh	21,989	1,346,971	1,368,960
West Bengal	441,272	0	441,272
Total	2,956,809	3,770,659	6,727,468

Source: NRSA and Associates (1996)

Both physical and chemical methods for reclamation of saline and sodic soils are not cost-effective; however, organic crop production is being promoted. Excess accumulation of salts hampers the growth and activity of soil microflora. It affects the growth of N_2 fixing and phosphate solubilizing bacteria which led to low fertility of soils. Due to increased quantity of salts, the microbial flora is worst affected, this also interfered with nitrogen fixing and phosphate solubilizing ability of bacteria. The microbial strains available as bio-fertilizers for different crops do not perform effectively under salt stress and their activity decreases when used in salt affected soils due to osmolysis. The soils of vast areas of Indo-Gangetic plains are sodic or saline–sodic. The halophilic plant growth promoting microbes have potential to ameliorate these soils. The halophilic bacterial strains can help in recovery of salt affected soils by directly supporting the growth of vegetation, thus indirectly increasing crop yields in salt affected soils. Halophilic plant growth promoting bacteria have high potential for remediation of salt affected soils and enhancing productivity of crops especially paddy and wheat.

22.3 Halophilic Bacteria

The existence of high osmotic pressure, ion toxicity, unfavourable soil physical conditions and/or soil flooding are serious constraints to many organisms and therefore salt affected ecosystems are specialized ecotones. The organisms found over there have developed mechanisms to survive in such adverse media and many endemisms. The halophilic microorganisms or 'salt-loving' microorganisms live in

Fig. 22.1 GypCal mobile app

environments with high salt concentration that would kill most other microbes. Halotolerant and halophilic microorganisms can grow in hypersaline environments, but only halophiles specifically require at least 0.2 M of salt for their growth. Halotolerant microorganisms can only tolerate media containing <0.2 M of salt. Distinctions between different kinds of halophilic microorganisms are made on the basis of their level of salt requirement and salt tolerance. The halotolerant grow best in media containing <0.2 M (~1%) salt and also can tolerate high salt concentrations.

Bacteria inhabiting soil play a role in conservation and restoration biology of higher organisms. The domain bacteria contain many types of halophilic and halotolerant microorganisms, spread over a large number of phylogenetic groups (Ventosa et al. 1998).

The halophiles are extremophiles that prosper in environments with very high salt concentrations as these are the salt-loving microorganisms that are distinguished by their characteristic of high salt requirement for growth and have developed physiological and genetic features to endure under hypersaline conditions. Halophiles or extremophiles include prokaryotic and eukaryotic salt-loving microorganisms which are capable of balancing high osmotic pressure. These organisms have developed a number of biochemical strategies to maintain cell structure and function under high salinity. The diversity among halophiles is regarded as the salt concentration, temperatures, pH conditions and redox conditions that the microorganisms are adapted. Halophiles play an important role in the carbon and phosphorus transformations under saline environments. With regard to the salt concentration, halophiles are able to produce hydrolytic enzymes in hypersaline environment that possess a potential importance in many of the industrial sectors. Moderately halophilic bacteria represent a group of microbes that is widely distributed in saline zones. These organisms show optimum growth at 5–15% NaCl. The extremely halophilic bacteria grow at salt concentrations more than 20% (w/v) to saturation. While slightly halophilic microorganisms can grow optimally in media containing 2–5% of NaCl concentration (Arora and Vanza 2017).

22.4 Plant-Microbes Interactions to Mitigate Salt Stress

It has been reported from several studies that inoculation with selected plant growth promoting rhizobacteria (PGPR) could be an effective tool for alleviating salinity stress in salt sensitive plants. Bacteria isolated from different stressed habitats possess stress tolerance capacity along with the plant growth promoting traits and therefore are potential candidates for seed bacterization. When inoculated with these isolates, plants show enhanced root and shoot length, biomass and biochemical levels such as chlorophyll, carotenoids and protein (Tiwari et al. 2011). Investigations on interaction of PGPR with other microbes and their effect on the physiological response of crop plants under different soil salinity regimes are still in incipient stage. Inoculations with selected PGPR and other microbes could serve as the potential tool for alleviating salinity stress in salt sensitive crops (Shrivastava and Kumar 2015).

Under stress conditions, the plant hormone ethylene endogenously regulates plant homoeostasis and results in reduced root and shoot growth. In the presence of ACC deaminase producing bacteria, plant ACC is sequestered and degraded by bacterial cells to supply nitrogen and energy. Furthermore, by removing ACC, the bacteria reduce the deleterious effect of ethylene, ameliorating stress and promoting plant growth (Glick 2007). The complex and dynamic interactions among microorganisms, roots, soil and water in the rhizosphere induce changes in physico-chemical and structural properties of the soil (Haynes and Swift 1990). Microbial polysaccharides can bind soil particles to form microaggregates and macroaggregates. Plant roots and fungal hyphae fit in the pores between microaggregates and thus stabilize macroaggregates.

Plants treated with exo-polysaccharides (EPS) producing bacteria display increased resistance to water and salinity stress due to improved soil structure (Sandhya et al. 2009). EPS can also bind to cations including Na+, thus making it unavailable to plants under saline conditions. Chen et al. (2007) correlated proline accumulation with drought and salt tolerance in plants.

Besides developing mechanisms for stress tolerance, microorganisms can also impart some degree of tolerance to plants towards abiotic stresses like drought, chilling injury, salinity, metal toxicity and high temperature. In the last decade, bacteria belonging to different genera including *Rhizobium*, *Bacillus*, *Pseudomonas*, *Pantoea*, *Paenibacillus*, *Burkholderia*, *Achromobacter*, *Azospirillum*, *Microbacterium*, *Methylobacterium*, *Variovorax*, *Enterobacter*, etc. have been reported to provide tolerance to host plants under different abiotic stress environments (Grover et al. 2011). Use of these microorganisms per se can alleviate stresses in agriculture, thus opening a new and emerging application of microorganisms. Microbial elicited stress tolerance in plants may be due to a variety of mechanisms proposed from time to time based on studies done. Production of indole acetic acid, gibberellins and some unknown determinants by PGPR results in increased root length, root surface area and number of root tips, leading to an enhanced uptake of nutrients, thereby improving plant health under stress conditions. Furthermore, production of proline, shoot/root length and dry weight was also higher in soybean plants inoculated with these isolates under induced salt stress. Likewise the impact of PGPR inoculation on growth and antioxidant status of wheat under saline conditions was studied by Upadhyay et al. (2011) who observed that co-inoculation with *B. subtilis* and *Arthrobacter* sp. could alleviate the adverse effects of soil salinity on wheat growth with an increase in dry biomass, total soluble sugars and proline content. It has been reported by Jha et al. (2011) that an endophytic bacterium *P. pseudoalcaligenes* in combination with a rhizospheric *B. pumilus* in paddy was able to protect the plant from abiotic stress by induction of osmoprotectant and antioxidant proteins than by the rhizospheric or endophytic bacteria alone at early stages of growth. Plants inoculated with endophytic bacterium *P. pseudoalcaligenes* showed a significantly higher concentration of glycine betaine-like quaternary compounds and higher shoot biomass at lower salinity levels. While at higher salinity levels, a mixture of both *P. pseudoalcaligenes* and *B. pumilus* showed better response against the adverse effects of salinity. Inoculation of *Azospirillum* strains isolated from saline or non-saline soil increased salinity tolerance of wheat plants; the saline-adapted isolate significantly increased shoot dry weight and grain yield under severe water salinity (Nia et al. 2012). The component of grain yield most affected by inoculation was grains per plant. Plants inoculated with saline-adapted Azospirillum strains had higher N concentrations at all water salinity levels.

22.5 Applications of Halophilic Bacteria

Halophilic bacteria provide a high potential for biotechnological applications for at least two reasons: (1) their activities in natural environments with regard to their participation in biogeochemical processes of C, N, S and P, the formation and dissolution of carbonates, the immobilization of phosphate and the production of growth factors and nutrients (Rodriguez-Valera 1993) and (2) their nutritional requirements are simple. The majority can use a large range of compounds as their sole carbon and energy source. Most of them can grow at high salt concentrations, minimizing the risk of contamination. Moreover, several genetic tools developed for the nonhalophilic bacteria can be applied to the halophiles and hence their genetic manipulation seems feasible (Ventosa et al. 1998).

Halophilic bacteria have the ability to produce compatible solutes, which are useful for the biotechnological production of these osmolytes. Some compatible solutes, especially glycine, betaines and ectoines, may be used as stress protectants (against high salinity, thermal denaturation, desiccation and freezing) and stabilizers of enzymes, nucleic acids, membranes and whole cells. The industrial applications of these compounds in enzyme technology are most promising. The other compatible solutes such as trehalose, glycerol, proline, ectoines, sugars and hydroxyectoine from halophilic bacteria showed the highest efficiency of protection of lactate dehydrogenase against freeze-thaw treatment and heat stress.

Also, halophilic bacteria produce a number of extra- and intracellular enzymes and antimicrobial compounds that are currently of commercial interest (Kamekura and Seno 1990). Halophilic bacteria can produce enzymes that have optimal activity at high salinity, which is advantageous for harsh industrial processes.

The application of halophilic bacteria in environmental biotechnology is possible for (1) the recovery of saline soil, (2) the decontamination of saline or alkaline industrial wastewater and (3) the degradation of toxic compounds in hypersaline environments. The use of halophilic bacteria in the recovery of saline soils is covered by the following hypotheses (Arora et al. 2014a, 2014b). The first hypothesis is that microbial activities in saline soil may favour the growth of plants resistant to soil salinity. The second hypothesis is based on the utilization of these bacteria as bio-indicators in saline wells. Indicator microorganisms can be selected by their abilities to grow at different salt concentrations. These organisms could indicate that well water could be used with producing low saline contamination of plants or soils which could be alleviated by the desertification of soil. The last hypothesis is the application of halophilic bacterium genes using a genetic manipulation technique to assist wild-type plants to adapt to grow in saline soil by giving them the genes for crucial enzymes that are taken from halophiles (Arora et al. 2017).

22.5.1 Liquid Bioformulations Halophilic Microbes for Amelioration of Sodic Soils

Salt tolerant (halophilic) bacterial strains of N-fixers and phosphate solubilization bacteria (PSB) were isolated from the salt affected soils at CSSRI, RRS, Lucknow. These strains were characterized for plant growth promotion and tested for their efficacy under different levels of salt stress. To enable the seed application of these promising selected strains of beneficial soil microorganisms, these were cultured in laboratory and prepared in suitable standardized media as liquid bioformulations, viz. Halo-Azo and Halo-PSB. These can be used either for seed/seedling root

Fig. 22.2 Halophilic PGPB formulations 'Halo-PSB, Halo-Azo and Halo-Zinc'

treatment or soil application. Application of these bioformulations helps to generate plant nutrients like nitrogen and phosphorus through their activities in the soil or rhizosphere and make available to plants in a gradual manner under salt stress. Also liquid formulations 'Halo-Zinc' and 'Halo-Mix' having salt tolerant strains of zinc solubilizers and consortia of N, P and Zn mobilizers, respectively, were developed and found to be effective under salt stress. These shall also help in maintenance of soil health, minimize environmental pollution and cut down on the use of chemicals in agriculture. They are affordable for most of the farmers who are small and marginal. Bioformulations are also ideal input for reducing the cost of cultivation and for promoting organic farming on salt affected soils (Fig. 22.2).

Under sodic and saline–sodic soils, the bioformulation has been tested at farm, validated at different farmer fields in 5 districts of salt affected areas. The seedling dip or seed inoculation with the bioformulation resulted in enhanced crop yields, management of soil health and stress regulation.

These liquid bioformulations are very beneficial for enhancing production of cereal crops mainly rice and wheat as well as vegetable crops. These can be easily used as seed treatment, seedling dip and soil application with FYM/manure. The packing of 100 ml bottle is sufficient for treating seeds of 1 acre land or root dip. It has been found to be very effective in sodic soil. There was increase in rice and wheat yield by 11.5 to 14 per cent under salt stress conditions in Indo-Gangetic plains (Fig. 22.3). This is the cheap and eco-friendly approach for bio-remediating salt affected soils and optimizing crop yields in the degraded lands.

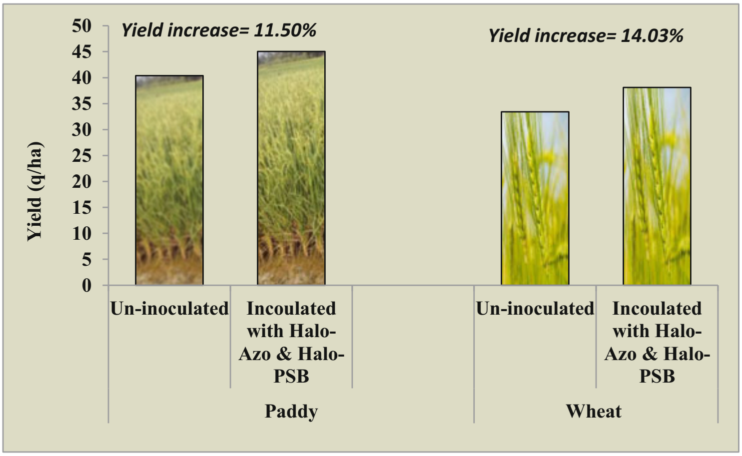

Fig. 22.3 Efficacy of liquid bioformulations of halophilic PGP strains on wheat and rice on sodic soils

22.6 Case Studies

Several researchers reported that introduction of these microbes is found very effective in salt affected soils to improve the crop productivity, quality of produce and soil properties (Kumar et al. 2014; Arora et al. 2016). Effect of integrated use of liquid bioformulations Halo-Azo, Halo-PSB and Halo-Zinc with 75% of recommended dose of NPK showed 6.7% increase in grain yield of salt tolerant short duration variety of paddy grown on sodic soil of pH 9.6 over 100% recommended NPK and zinc sulphate (Singh and Mishra 2018). In coastal saline soils, highest grain yield of 5.12 t ha^{-1} of rice variety 'Sumati' was reported with combined application of liquid bioformulations Halo-Azo and Halo-PSB compared to grain yield of 4.69 t ha^{-1} in uninoculated control, indicating yield enhancement of 9.1% (Sarangi and Lama 2018).

Exploitation of *Azotobacter* and phosphate solubilizing bacteria as biofertilization has enormous potential in improving the crop productivity and soil fertility in sodic soil condition. It was observed that potential salt tolerant variety of paddy in association with halophilic beneficial microbes together can play a greater role to improve the productivity of paddy as well as soil fertility. These bioformulation showed significantly increased plant growth in terms of germination per cent, plant establishment per cent, plant height, no. of effective tillers/hill, no. of grains /panicle, length of panicle, test weight grain and straw yield. Alone as well co-inoculation of Halo-Azo and Halo-PSB increased the productivity of CSR-36 significantly (Sahay et al. 2018).

In a study to ascertain the response of non-symbiotic microbial inoculants on growth, yield and quality of fennel (*Foeniculum vulgare*) grown in partially reclaimed sodic of Uttar Pradesh, it was observed that inoculation of phosphate solubilizing bacteria or in combination with *Azotobacter chroococcum* was superior resulting in 14%–15% increase in seed yield (Garg et al. 2000). Application of fertilizers (80 kg ha^{-1} N + 25 kg ha^{-1} P) with inoculants had an additive effect on plant growth. An increase in availability of soil P (41%–44%) and essential oil content (10%–14%) was also noticed (Bhadauria et al. 2010).

22.7 Microbial Inoculation Influencing Soil Properties

The application of liquid bioformulations of halophilic plant growth promoting bacteria has the potential to improve growth and yield of crops under salt stress and they were also found to play role in soil health improvement as observed in soil after harvest of the crop (Table 22.2). There was substantial improvement in soil pH and exchangeable sodium content. Build-up of soil organic C and N apart from improvement in microbial biomass C and dehydrogenase activity was observed with application of liquid bioformulations.

It has been reported from experiment conducted on sodic lands of Etawah district that combined use of organic amendments, bioinoculants and gypsum brings significant changes in soil properties (Rai et al. 2010). Soil ESP was lowered with integrated use of gypsum+ pressmud or water hyacinth with or without bioinoculant. The effect of bioinoculant on the reduction of soil pH was marginal which is attributed to the activation of autochthonous microorganisms on addition of organic amendments. Soil organic carbon, available nitrogen and available phosphorus

Table 22.2 Effect of bioformulations use on sodic soil properties after harvest (initial soil pH = 9.42)

Treatment	pH(1:2)	EC(dS/m)	OC(%)	Exch.Na(mg/kg)	ESP	AvN(kg/ha)
Control (FYM)	9.24	0.432	0.28	338	44	103
FYM + Halo	8.94	0.318	0.35	266	42	119
Azo						
FYM + Halo	9.12	0.364	0.33	272	43	113
PSB						
FYM + Halo	9.18	0.385	0.31	282	43	121
Azosp						
FYM +	8.91	0.322	0.38	238	41	123
Consortia						

Av P(kg/ha)	MBC(μg/g)	DHA(μgTPF/g/d)
10.8	44	10
11.4	55	13.9
15.1	52	12.2
14.4	58	13.2
15.6	61	14.8

content increased up to 20, 9.9 and 16.8%, respectively, with the inoculation of halophilic bioformulations (Sahay et al. 2018).

22.8 Vesicular Arbuscular Mycorrhiza (VAM)

Vesicular arbuscular mycorrhizal fungi commonly called as VAM occur naturally in saline environment. Several researchers investigated the relationship between soil salinity and occurrence of mycorrhizae on halophytes. They reported that the number of VAM spores or infectivity of VAM fungi changed with change in salt concentration (Juniper and Abbott 1993). The stresses due to saline soils effect the growth of plants, fungus, or both.

VA mycorrhizal fungi most commonly observed in saline soils are *Glomus* spp. (Juniper and Abbott 1993) and this suggests that this may be adapted to grow in saline conditions, but ecological specificity has not been demonstrated. There is evidence that VAM species distribution is markedly changed with increased salinity (Stahl and Williams 1986). Aliasgharzadeh et al. (2001) observed that the most predominant species of Arbuscular mycorrhizal fungi (AMF) in the severely saline soils of the Tabriz plains were *Glomus intraradices*, *G. versiform* and *G. etunicatum*. There are few studies indicating that mycorrhizal fungi can increase growth of plants growing in saline habitats (Yadav et al. 2017). VA mycorrhizal fungi may have the ability to protect plants from salt stress, but the mechanism is not fully understood. The few data available at present suggest that fungi do have a potential to enhance plant growth by increasing the uptake of the nutrients. The efficacy of three species of AMF—*Glomus mosseae*, *G. intraradices* and *G. claroideum*—were tested to alleviate salt stress in olive trees under nursery conditions (Porras-Soriano et al. 2009). The authors observed that *G. mosseae* was the most efficient fungus in terms of olive tree performance and particularly in the protection offered against the detrimental effects of salinity. These findings suggest that the capability of AMF in protecting plants from the detrimental effects of salt stress may depend on the behaviour of each species.

22.9 Cyanobacteria

A halotolerant, heterocystous and nitrogen fixing cyanobacterium *Nostoc calcicola* Breb. grow successfully on saline–alkaline soils of Eastern Uttar Pradesh (Singh and Singh 2015). A study was conducted to assess the effect of cyanobacteria on the reclamation of saline–alkaline soils by observing the changes in soil properties inoculated with cyanobacteria and gypsum. It was reported that in treated soils significant decrease in pH, ECe and Na^+ has been observed with cyanobacterial application. There also occurs a significant increase in organic carbon. *N. calcicola* + gypsum seem to be a suitable combination for reclamation of saline–alkaline soils.

In reclamation of saline–alkaline soil, the conversion of Na^+ clay into Ca^{2+} clay and leaching of excess Na^+ was noted. Following the addition of gypsum and halotolerant cyanobacterial (*N. calcicola*) to sodic and saline soil, soil microbial biomass (SMB) and respiration rate increased despite adverse soil environmental conditions (Vanessa et al. 2009). A significant improvement in soil properties has also been observed after cyanobacterial growth. Alkaline soils with high pH values and Na + content favour the growth of diazotrophic cyanobacteria with a consequent decrease in pH. Singh (1961) also reported fall in soil pH from 9.2 to 7.5 with cyanobacteria. Certain organic metabolites produced by cyanobacterial activities are also released in the soils which are responsible for maintaining the fertility of soil year after year (Ladha and Reddy 1995). The presence and succession of diazotrophic cyanobacteria in alkaline soil was reported by Singh (1961) and Singh et al. (2014a, 2014b). Jaiswal et al. (2010) also suggested *N. calcicola* as bioameliorating agent for saline–alkaline soil. Addition of *Nostoc calcicola* biomass to the saline/alkaline soils decreased the pH content and hence improved soil properties. The dominance of *N. calcicola* in saline/alkaline soils may be due to its salt tolerance, which suggests that *N. calcicola* could be a better phytotechnological approach for soil reclamation. Singh (1961) suggested that cyanobacteria could be used to reclaim alkaline soils because they grow successfully on saline/alkaline soils where most plants fail to grow. Pandey et al. (2005), Jaiswal et al. (2010) and Murtaza et al. (2011) have also suggested the role of cyanobacteria in reclamation of saline–alkaline soils.

22.10 Future Challenges for Salt Stress Mitigation Through Halophilic Microbes

The identified halophilic plant growth promoting microbes need to be applied in agriculture to enhance crop yields under salt stress conditions. Development of biological products based on beneficial halophiles can extend the range of options for maintaining the healthy yield of crops in salt affected soils. In recent years, a new approach has been developed to alleviate salt stress in plants, by inoculating crop seeds and seedlings with salt tolerant plant growth promoting microbes. Thus, there is great opportunity for halophilic PGPR for their successful application in agriculture especially in Indo-Gangetic plains of UP. The microbial formulation and application technology are crucial for the development of commercial salt tolerant bioformulation effective under salt stress conditions. Bioformulations offer an environmentally sustainable approach to increase crop production and health. Apart from microbial reclamation, improving fertility of salt stressed soils is another aim to be focused on. It has been observed that inoculation with mixed strains was more consistent than single strain inoculations. Studies on the detailed mechanism of mycorrhizal fungi associated plant growth under salt stress are lacking and this needs to be explored. The promising approach toward tackling the problem of soil salinity utilizing beneficial microorganisms including halophilic PGPR will make the greatest contribution to the agricultural economy as they provide cheap and eco-friendly approach to mitigate salt stress.

22.11 Conclusion

One of the most important abiotic stress constraints to agricultural production is the salt stress. Plant-associated microorganisms can play an important role in conferring resistance to abiotic stresses including salinity. These organisms could include rhizoplane, rhizosphere and endophytic bacteria, cyanobacteria and symbiotic fungi and operate through a variety of mechanisms like triggering osmotic response, providing growth hormones and nutrients to plants.

Microbial inoculation to alleviate stresses in plants could be a more cost-effective environmental friendly option which could be available in a shorter time frame. The halophilic plant growth promoting microbes not only alleviate salt stress, enable plant growth under salt but also improve soil health.

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Role of Zeolites in Improving Nutrient and Water Storage Capacity of Soil and Their Impact on Overall Soil Quality and Crop Performance

23

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Abstract

The zeolites application can improve the overall soil quality due to their unique cation exchange, adsorption, hydration–dehydration, and catalytic properties. Globally, several studies have been carried out to investigate the feasibility of using them to enhance the crop yields, nutrient use efficiency, and water use efficiency. These are microporous, crystalline, hydrated aluminosilicates of alkali and alkaline materials with high CEC and internal pore structure with an ability to hold nutrients and water molecules in them. These can hold nutrients such as NH_4^+ and K^+ ions, which consequently release slowly for continuous uptake by plants. Hence, they can be used as slow release fertilizers, if applied along with N and K fertilizers. Mainly zeolites reduce the N losses that occur through ammonia volatilization and nitrate leaching. Research studies that were carried out in the laboratory, greenhouse and field experiments with different crops and environments showed that the zeolite was found to be very effective towards reducing the ammonia losses caused due to volatilization and increased the efficiency of N utilization. There are also studies that have formulated fertilizers with zeolites and reported that compounded fertilizers with zeolites are proved to enhance nutrient use efficiency. Recently, nano-zeolite of nano size has gained more importance towards enhancing crop production. Zeolites application enhances the water retention in soil. So, application of zeolites is proven better for increasing the water productivity in addition to nutrient use efficiency. The zeolites are found very effective in treating waste water and the treated zeolite can in turn be used as slow release fertilizer as they are rich source of nutrients.

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Overall, these naturally occurring materials are found excellent in maintaining soil quality.

Keywords

Ammonium volatilization · Nutrient use efficiency · Soil quality · Water use efficiency and Zeolites

23.1 Overview of Zeolites

The unscientific land management, deforestation, change in land use, soil erosion, and waste disposal in addition to intensive farming practices have virtually mined nutrients from the soil. The impact of intensive farming practices, particularly in wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) has resulted in poor soil quality in India. The targetted N:P:K ratio that need to be followed is 4:2:1, however, there is poor and asymmetry consumption ratio of6.2:4:1 (N:P:K) in 1990–1991 that has widened to 7:2.7:1 in 2000–2001 and now 5:2:1 in 2009–2010. Although the use of fertilizers has increased to several fold and accordingly, food grain production also increased with time, yet, the number of elements deficient in Indian soils increased from one (N) in 1950 to nine (N, P, K, S, B, Cu, Fe, Mn, and Zn) in 2005–2006. The estimated gap between removals and additions of nutrients is reported to be 8 to 10 Mt. N + P2O5 + K2O per year (Tandon 2007). Thus, it is peak time to address this soil fertility depletion as research and practice during the last 20 years strongly suggests that agriculture should be managed in such way that it should ensure food and nutritional security in addition to minimizing the effects of climate change(Rakshit et al. 2018). Further, in recent decades, urbanization and industrialization are spreading enormously thereby the soils are under prodigious pressure to meet the food demand and food quality. In this context, zeolites are the naturally occuring minerals that are environmental friendly, ubiquitous, and inexpensive. They can be used in agricultural activities as they act as soil conditioners to improve soil physical and chemical properties including infiltration rate, saturated hydraulic conductivity, water holding capacity, and cation exchange capacity.

Zeolites are crystalline, hydrated aluminosilicates with three-dimensional structure and generally found in igneous, metamorphic, and sedimentary environments (Rehakova et al., 2004). They often occur as large and beautiful crystals in different colors (Plate 23.1). The primary building units in their structure consist of $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ tetrahedra linked by the sharing of all oxygen atoms. These units get connected to several tetrahedral that results in the formation of cages/cavities in their framework. Nearly 235 distinct zeolite framework types have been identified and assigned a three-letter code by the International Zeolite Association. The generic mineralogical formula for the ore is $M^{m+}{}_{n/m}[Si_{1-n}\ Al_nO_2]\ nH_2O$, where M represents the cation that in most cases is Na^+, K^+, Mg^{2+}, Ca^{2+}(Gelves Diaz 2017). These are most useful because of their high cation exchange capacity (200–300 meq 100^{-1} g) (Palanivell et al., 2016). For instance, the ion-exchange capacity of some of naturally

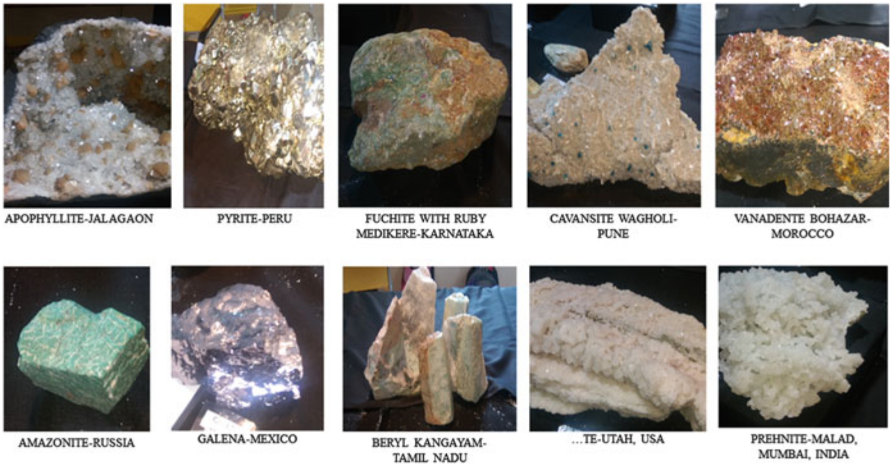

Plate 23.1 Photograhs of zeolite from different locations

occuring zeolites such as analcine, chabazite, clinoptilolite, erionite, heulandite, mordenite, and philipsite is 4.54, 3.84, 2.16, 3.12, 2.91, 4.291, and 3.31 meq/g, respectively. The unique feature of zeolites that fits best in agriculture is due to its ability to lose and gain water reversibly (Leggo et al., 2006). Among naturally occuring zeolites, clinoptilolite is the most well known and commonly used zeolite with wide applicability. It belongs to the heulandite group and comprises a two-dimensional channel system (a 10-ring system (0.31 nm $\times$ 0.75 nm), an 8-ring system (0.36 nm $\times$ 0.46 nm), and channels (0.28 nm $\times$ 0.47 nm) (Koyama and Takéuchi 1977). The western United States, Bulgaria, Hungary, Japan, Australia, China, and Iran are the leading countries with huge deposits of zeolites (Mumpton, 1999). According to U.S. Geological Survey (2016), estimated total world reserves of zeolites are large with China leading the market with approximately 75% of the total production, followed by Korea (8%), USA (3%), and Turkey (2%). There are more than 50 and 150 natural and synthetic forms, respectively (Jha and Singh, 2016; Virta 2002). Based on pore size, they are classified into the following categories: extra-large pore zeolites ($\theta \geq 9$ Å), large pore zeolites (6 Å $< \theta < 9$ Å), medium pore zeolites (5 Å $< \theta < 6$ Å), and small pore zeolites (3 Å $< \theta < 5$ Å), depending on the access to the inner part using 8, 10, or 12 atoms oxygen rings, respectively(Melo et al., 2012). Also, they differ from one another in the content of Si and Al. They act as molecular seive as the size of the channels in zeolite control the size of the molecules or ions that can pass through them thus exihibits selective absorption. These are widely used as commercial adsorbents. They are very stable minerals with good structural stability thus shows good stability against weathering, impact, and abrasion tests (Ok et al., 2003). Hence, they have wide applicability (Fig. 23.1). They show high affinity for ammonium (NH_4^+) and other cations and widely used to remove $NH_4^+$from municipal, industrial, and aqua cultural wastewaters. Extensive literature is available regarding the capacity of

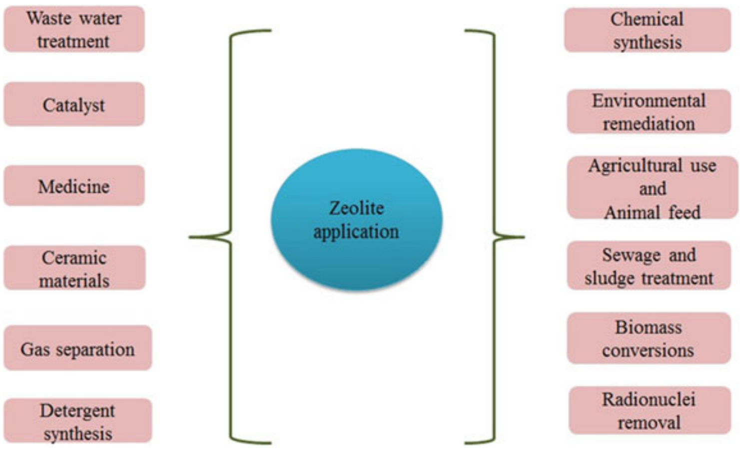

Fig. 23.1 Various applications of zeolite

zeolites to remove $NH_4^+$from wastewaters. Zeolites play a major role in remediating heavy metals in soils by adsorbing different cations such as cesium (Cs) and strontium (Sr), cadmium (Cd), lead (Pb), nickel (Ni), manganese (Mn), zinc (Zn), chrome (Cr), iron (Fe), and copper (Cu). In India, an area of 4.2 million km^2 situated between latitudes 0° and 20° S and longitude 70° and 84° E of the central Indian basin contained zeolites. In addition to Maharashtra, zeolite occurs as filling in the amygdular cavities in Deccan trap basalts of Gujarat, Madhya Pradesh, and Karnataka too. Different substances are adsorbed at very different rates in the same zeolite, for example, chabasite takes up hydrogen and water vapor at room temperature in a few minutes, whereas iodine or mercury is taken up at a measurable speed only at temperatures above 100 °C–200 °C. Zeolites differ among themselves toward one and the same substance adsorption.

23.2 Application on Zeolites on Crop Performance

The world's human population is expected to reach 9.1 billion people by 2050. Thus, the crop production may rely heavily on synthetic inputs to meet the food demand. This will cause damage to the soil and environment such as nitrate loading in water resources, GHG emissions, etc. The increase of hypoxic zones in the Gulf of Mexico is due to the loading of N and P in Midwestern states of United States(Rabalais et al., 2002). Also, the use of synthetic agrochemicals for plant nutrition or for disease management, pests, weeds, etc. is responsible for environmental pollution and ecological issues. So, zeolites are found to reduce the environmental pollution apart from increasing use efficiency through controlled release of fertilizers and pesticides, including a reduction in the amount of active ingredients (De Smedt et al., 2015). Infact, due to improper nutrient management, the soil fertility has largely deprived and the deprived soil fertility is one of the major limitations to achieve global food production and food security.

Zeolite can enhance the agricultural production as their application aids in boosting upwater retention and improving fertilizer use efficiency while minimizing nutrient losses such as ammonia loss and nutrient leaching (Ozbahce et al., 2015). However, zeolites alone cannot meet the crop nutrient demand; these help in improving the nutrient use efficiency when applied along with fertilizers. They improve the nutrient use efficiency by retaining the nutrients and releasing them at a slow rate. Zeolites are well known for increasing soil N and K availability. However, they can also increase the soil P availability, if applied along with phosphate rock. They react with phosphate rock substituting calcium in exchange of ammonia thereby increasing the P solubility(Shokouhi et al., 2015). Several studies indicated that application of zeolite along with fertilizers showed positive effects on crop performanance and yield (Table 23.1). Extensive research reported

Table 23.1 Impact of zeolite application in different soil types on crop yield

Crop	Best treatment	Soil type	Impact on yield	Reference
Sunflower	80 kg N ha^{-1} (urea) + 50 kgN ha^{-1} (composted manure) + 21% zeolite	Sandy loam soil	Yield increase by 10.02% in first year (2008) and 25.10% in second year (2009)	
Rice	N application rate of 80 kg $ha^{-1}$and Z application rate of 4 t ha^{-1}	Silty clay soil	38.03% increase in yield as compared to control	Sepaskhah and Barzegar (2010)
Lettuce, tomato, and rice	Zeolite enriched withH_3PO_4 + apatite	Pot study carried with an inert substrate	Increase of 34% of lettuce DM yield, 50.3%of tomato DM yield and observed DM yield decrease in rice	
Rice	Continuous flooding with phosphorus rate of 60 kg ha^{-1} and zeolite rate of 15 t ha^{-1}	Clay loam	Highest grain yields in both years, being 12.0% and 8.9% in 2016 and 2017	Zhang et al. (2019)
Dragonhead	Combinations of zeolite and nitroxin × phosphate barvar-2	–	Could significantly improve essential oil yield	
Spring barley, Sugarbeet, spring wheat	Use of mechanically activated zeolite into the soil in doses of 10 and 15 t ha^{-1}	Medium thick heavy loamy	The average annual grain yield gain was 0.3 and 0.5 t/ha, and the payback of 1 ton of zeolite by additional harvest 0.11 and 0.09 t/ha in grain units, respectively	Bikkinina et al. (2020)
Maize	Nitrogen @ 200 kg ha^{-1} + zeolite @ 7.5 t ha^{-1}	Loamy sand	Higher grain yield (46.80 g pot^{-1})as compared to control (14.86 g pot^{-1})	

that zeolite mixed with urea was able to enhance rice grain yields in flooded paddy fields by minimizing the N losses (Kavoosi, 2007; Gevrek et al., 2009; Sepaskhah and Barzegar, 2010). With application of 5–15 t ha zeolite on silty loam soil rice grain yield increased by 14.9% compared to the control treatment (Chen et al., 2017). Zeolite can also improve the use efficiency of micronutrients if applied with micronutrient fertilizers. Shahsavari et al. (2014a, b) reported 43.8%, 73.9%, and 30.0% increase in grain yield, biological yield, and harvest index, respectively, in Brassica napus plants with 15 t ha^{-1} zeolite addition along with 0.1% Zn sulfate. Likewise, Malekian et al. (2011) reported that application of 60 g kg^{-1} of zeolite-clinoptilolite to maize crop resulted in higher grain yield, grain N content, dry matter, and N uptake. To attain, application of 5 t ha^{-1} zeolite along with 4.5 t ha^{-1} residues in corn and sorghum crops resulted in highest forage yields also, observed lowest cadmium concentrations in the tissue of forage (Najafinezhad et al., 2014) in a double-cropping system. Recently, it was found that 10 Lha^{-1} humic substance with 20 kg zeolite carrier for every liter humic substance resulted in 30% increment of oil palm fresh fruit bunch (Suwardi et al., 2020). Hence, soil application of zeolites helps in retaining essential nutrients in the root zone, allowing them to be used by plants when required. Consequently, this leads to a more efficient use of fertilizers by reducing their normal application rates, by prolonging their activity, or finally by producing higher yields (Leggo et al. 2006).

Zeolites can be sucessfully used in agriculture either for plant growing on open field, or as substrate for application under greenhouse conditions (Tsintskaladze et al., 2016). Zeolites in combination with peat moss and perlite found to be good substrate for pot cultivation (Eghtedary-Naeini et al., 2016). It was found that 25% zeolite in perlite substrate was able to give good dry biomass in pepper plants (Aghdak et al. 2016). However, Djedidi et al. observed that tomato plants grown in perlite and zeolite at 2:1 ratio had the best distribution of fruit size; though total soluble solid and the highest fruit dry matter. Other results also showed that using perlite and zeolite as the growing media produced the highest fruits number and yield. In fact, zeolites also play a major role as substrates in hydroponics. Across the agroecosystems, several researchers have reported the promising results of zeolites in increasing N, P, and K, micronutrients, and water use efficiency.

23.3 Role of Zeolite Application on Soil Quality

Based on the projected world population that is likely to increase to 9.5 billion by 2050, there will be a necessity to increase the agricultural production by ~70% between 2005 and 2050. Soil degradation, characterized by decline in quality and decrease in ecosystem goods and services, is a major constraint to achieving this targetted increase in agricultural production. Soil degradation is considered as twenty-first century global problem that is especially severe in the tropics and sub-tropics. Among the major soil degradation processes are: accelerated erosion, depletion of the soil organic carbon (SOC) pool and loss in biodiversity, loss of soil fertility and elemental imbalance, acidification, and salinization. However, soil degradation trends can be reversed by conversion to a restorative land use and adoption of recommended management practices such as minimizing soil erosion, creating positive SOC and N budgets, enhancing activity and species diversity of soil biota (micro, meso, and macro), and improving structural stability and pore geometry. Improving soil quality (i.e., increasing SOC pool, improving soil structure, enhancing soil fertility) can reduce the risks of soil degradation (physical, chemical, biological, and ecological) while improving the environment. Soil quality has been defined as the "capacity of the soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". In the past, soil quality was understood as the inherent capacity of the soil to supply essential plant nutrients. Later, it was viewed as an abstract characteristic of soils that could not be defined because of its dependence on external factors such as land use and soil management practices, ecosystem and environmental interaction, socioeconomic and political priorities, and so on. Using indicators that can measure changes in its attributes or attributes of the ecosystem, soil quality can be measured. These indicators are grouped into 4 categories as visual, chemical, physical, and biological indicators. Soil erosion is one of the most complicated problems that removes and redistributes the soil. This results in reducing soil fertility. Several compounds/amendments that can improve soil quality by reducing soil erodibility were thoroughly researched and found that zeolite is a very effective mineral that can reduce the erodibility by improving soil hydro-physical properties. Also zeolite plays an important role in reducing run off and soil loss. In a study with zeolite under rainfall simulation revealed that application of 750 g m^{-2} zeolite in silty loam soil increased the beginning time of runoff by 644% thus found to be an effective amendment to control soil erosion in steep and degraded rangelands. Interestingly, spraying of zeolite powder on the soil surface created a relatively protective layer, and considerably reduced the loss of top soil against splash erosion.

A study carried in north coast of Cuba, Villa Clara province, found that application of sugarcane filter cake and natural mineral along with chemical fertilizers has resulted in positive impact on degree of soil aggregation, water-stable aggregates, permeability, lower plastic limit, pH in water, pH in KCl, organic matter, assimilable P_2O_5 and K_2O (Cairo et al. 2017). Najafi-Ghiri (2014) conducted incubation study with zeolite on soil K and found that zeolite used in their study had a high ratio of exchangeable to soluble K (6100:80), suggesting a high tendency of zeolite for K adsorption. Mirzaei et al. (2015) studied effects of natural zeolite and nano-zeolite on plant residues and observed significant results in the increment of organic carbon and soil aggregation.

The pioneer studies on zeolite have pointed out that it takes care of all the properties that acts indicators of soil quality and thus its application improves overall soil quality. Ghaemi et al. opined that the use of principal components can contribute to the assessment of soil quality and the sustainable management of an agricultural system. The properties that best demonstrate the qualities of indicators of soil quality are organic matter, stable aggregates, degree of soil aggregation, permeability log 10 K, and lower plastic limit. Martelletti et al. studied the impact of zeolite application on forest restoration and found that zeolite application

Table 23.2 Performance of zeolite on soil quality parameters

Soil quality parameter	Influence of zeolite	Reference
Soil inorganic N content	As compared to zero Z application, 5 and 10 t Z ha^{-1} application improved NH_4^+-N content by 27.4% and 41.5%, respectively and NO_3-N content by 15.1% and 24.7%, respectively	
Soil available K	Zeolites 5 $t.ha^{-1}$ + cattle manure 5 $t.ha^{-1}$ has resulted in highest avilability of K (0.49 $cmol.kg^{-1}$) in Alfisols	
Soil aggregation	Addition of 10% artificial zeolite boosted the mean weight diameter and saturated hydraulic conductivity with an decrease in exchangeable sodium percentage and thus reduced soil aggregate dispersion in sodic soil	
Saturated hydraulic conductivity (ks)	Application of natural chabazite @ 10 kg/m^2could increase the residual water content by 1.2 ± 0.4% throughout the summer droughts and 45% increase in ks	Colombani et al. (2014)
Bulk density	Application of the zeolite in both years reduced the apparent bulk density by 10% and increased EC by 6%	
pH	Adding natural zeolite (NZ) to salinity soil (treatment NZNaCl and $NZNa_2SO_4$) increased air fresh weight (AFW) and both total dry weight (TFW) in radish (Raphanus sativus L.)	Noori et al. (2006)

influenced N content, exchangeable K and Mg/K in the three study years, with higher values of N and exchangeable K in the zeolite amended treatment and higher values of Mg/K in the non-amended treatment. The positive impact of zeolite on soil quality indicators is given in Table 23.2.

It was found that the soil bulk density decreased from 1.42 g cc^{-1} (without zeolite) to 1.02 g cc^{-1}due to zeolite application of 9 t ha^{-1}(Pandit et al., 2020). The total N due to fresh straw, 300 kg/ha urea and 300 kg/ha zeolite application in soil resulted in 0.467% as compared to 0.159% in without application. Nearly 3 times increase in total N was observed due to application of zeolite in combination with urea and fresh straw (Wulandari et al., 2019). Soil quality can be evaluated by exploring a range of soil physical, chemical, and biological properties. Zeolite can also enhance the carbon use efficiency by reducing gaseous emissions. The natural clinoptilolite zeolite showed adsorption potential for CO_2 and NH_3 evolved during co-composting of grape and tobacco waste to 31% and 100%, respectively. Ferretti et al. (2017) studied natural chabazite and NH_4^+-enriched chabazite on gaseous emissions (CO_2, N_2O, NO_x, and NH_3) with urea application and found that immediate emissions after fertilizer application were reduced in soils amended with natural chabazite as compared to NH_4^+- enriched chabazite. However, NH_3 emissions were higher in NH_4^+-enriched zeolites amended soil, but if the amendment is performed without further N inputs, the emissions can be significantly lowered with respect to a conventional urea fertilization. The study revealed an higher carbon use efficiency with the use of both the zeolites.

Most of the literature regarding soil column leaching experiment showed that zeolite application has sucessfully reduced the content of nitrogen and potassium in leachates.

23.4 Effect of Zeolite Application on Nutrient Retention and Release Chemistry in Different Types of Soils

The nutrient retention and release characteristics of zeolites can be better understood using batch and column studies. The major difference between batch and column experiments is that batch studies typically overestimate concentrations because they brought to equilibrium under natural conditions. Batch experiments could be cheaper and less time-consuming, but do not provide change in solute concentration over time. Ultimately, the column experiments could be more costly in terms of time and analysis but they provide information that is closer to reality. A study showed that natural zeolites charged with swine manure could be a viable option to retard excess leaching of nutrients in agricultural lands and both batch and column experiments should be performed together to cross-check and validate the obtained results. Huang et al. (2015) reported that $NH_4{}^+$ -N adsorption on zeolite is affected by the presence of competitive cations (i.e., Na^+, K^+, Ca^{2+}, and Mg^{2+}) that occupy the available ion-exchange sites on the zeolites. In depth research suggests that the capacity to remove cations depends on the zeolite particle size. The particle sizes of 1.00 to 3.00 mm are effective in improving the chemical conditions of the soils, by reducing N volatilization up to 57%. However, particles below 1 mm show high Na^+ and K^+ retention (Soca and Daza-Torres 2016). In several studies, it was found that there was increase in ammonium adsorbed with the increasing zeolite dosage. Ammonium adsorption has reached to a peak of 18.6 mg/g with dosage of 15 g/L, and correspondingly, ammonium removal rate was 33.1%. It is clear that increasing dosage continuously had negative effects on the increase of ammonium adsorbed onto unit of zeolite which may be attributed to the great concentration pressure at equilibrium (Nan et al., 2019). Batch experiment carried with 20 g of zeolite with 100 mL of 200 mg/L concentration of K and Zn showed a removal effeciency of 78%. It was also found that the adsorption isotherms of the zeolite in the study followed the Langmuir model and shown well fit by a pseudo-second-order kinetic model showing a high correlation coefficient ($r^2 > 0.99$) for single-element of K and Zn (Rocha and Zuquette 2020). Jaskunas et al. (2015) observed that during initial phase of adsorption process, the adsorption process was very fast which later adsorption continues at a slower rate. This behavior is due to availability of more sites at the beginning and as it progresses; these sites become occupied, making them difficult to access and causing a repulsion effect between the adsorbed ions and the remaining ions in solution. The nano-sized zeolite is capable of retaining Zn and releases at slow rate into the soil solution, hence may serve as a slow release Zn fertilizer and improve use efficiency by crops. With the application of zeolite @ 10 and 15 t ha-1, there was increase in mobile phosphorus avaialability to plants by 8 and 10 mg kg-1. Similarly, the increase in exchnageable K was about 5 and 6.6 mg kg^{-1}, respectively. Also, the growth acceleration of microbial biomass was found to be 15.5 mg per 100 g*h (Bikkinina et al., 2020).

Pioneer studies showed that modification of zeolite can improve and enhance the uptake of cations. The modification process includes pretreatment by grinding and sieving, modifying by sodium salt and finally calcination. These modifications resulted in improved pore size and surface area of zeolite, which eventually increased the cation uptake by zeolite. Heulandite is a (Ca, Na) 2 - 3Al3 (Al, Si) 2Si13O36 - 12H2O, Hydrated calcium sodium aluminum silicate is one of the naturally existing zeolites. It was subjected to activation to get the best results for the adsorption of ammonium by salt treatment and found that the temperature of 70 °C, stirring time of 30 min, and 1 mol/L concentration of NaCl were the most effective in adsorption of ammonium ions on natural heulandite.

23.5 Zeolite Application and Water Storage, its Retention and Productivity in Different Types of Soils

Zeolites application can improve the soil physical properties. They may hold water more than half of their weight due to high porosity of the crystalline structure. Zeolites assure a permanent water reservoir by reducing prolonged moisture dry periods. They also promote a rapid rewetting and improve the lateral spread of water into the root zone during irrigation. This also results in reducing the amount of water needed for crop production. Amendment of sand with zeolite increases available water to the plants by 50%. Substrate containing 30% zeolite was used to grow tomato in pots and found that there was an increase in their water holding capacity (260%), total porosity (8.47%), bulk density (212%), and particle density (230%) as compared to substrates with zeolite.

In case of maize grown on loamy sandy soils, application of zeolite @ 7.5 t ha^{-1} recorded lowest bulk density (0.97 g cc^{-1}) and increased water holding capacity to 48.54%. The high porosity of zeolite structure helps improve soil structure and increase aeration without clogging soil pores. Because of their porous nature zeolites can hold more than their weight in water, and in soil can act as a reservoir providing a prolonged water supply. Zeolites can improve water infiltration into soil, and speed rewetting and lateral spread of irrigation water in the root zone. Improved soil water holding capacity (WHC) is important for crop production, especially in arid and semi-arid regions where it increases water efficiency from irrigation. For example, soil treatment with the zeolite mordenite, which has a WHC of 121% (holding 1.21 times its own weight in water), increased soil water infiltration by 7–30% on a gentle slope and up to 50% on a steep slope, and reduced runoff after precipitation. Also, mixing clinoptilolite, another zeolite, at a rate of 10% by weight to a sandy soil resulted in a 20% increase in WHC compared to untreated soil (Bigelow et al., 2001). Zeolite application could be combined with irrigation technology for improved water use efficiencies in the field, especially in dry regions (Mpanga and Idowu, 2020). Water retention at matric potentials of −100 and −300 kPa was greatest for a mixed zeolite rate of 44.8 Mg ha^{-1} compared with a lower zeolite rate and a control.

Results reported by Xiubin and Zhanbin show that soil treated with zeolite, compared to normal soil, increases infiltration by 7–30% on gentle slope land and more than 50% on steep slope land. In addition, soil amended with zeolite

Table 23.3 Influence of zeolite application on soil physical parameters

Zeolite	Soil type	Change in soil physical properties	Reference
Zeolite-clinoptilolite (50%) + calcium carbonate (47.5%) + leonardite extract (2%) + Ascophyllum nodosum extract (0.5%)	Sandy loam	Lower bulk density was observed (1.54 g cm^{-3}) as compared to control (1.57 g cm^{-3})	Długosz et al. (2020)
Zeolite application @ 20 t ha^{-1}	Humus sand	Moisture content and water holding capacity were increased to the extent of 8.3 and 6.23% while there was decrease in water permeability to the extent of 8.65% as compared to control	Tállai et al. (2017)
NH_4^+-enriched zeolite applied in a dose of 5 kg/m^2	Silty clay soil	Zeolite amended soil exhibited a slightly higher Ks (4.5 cm/d) with respect to the unamended one (2.9 cm/d) and an increased AWC (11% more).	Colombani et al. (2014)
Zeolite application rates of 0 (control) and 8 g kg^{-1}	Loam soil	Zeolite application resulted in the decrease of values of θim and α. the maximum and minimum values of θim were 0.211 cm3 cm^{-3} and 0.059 cm3 cm^{-3}, respectively. The maximum and minimum values of D_h were 2.26 cm2 min^{-1} at rate of 8 g kg-1 soil and 0.037 cm^2 min^{-1} at control, respectively	Fooladi Dorhani and Sepaskhah (2017)

increased soil moisture by 0.4–1.8% in extreme drought condition and 5–15% in general situation (Table 23.3).

23.6 Zeolites as Soil Amendments and Slow Release Fertilizers

There is tremendous use of fertilizers in agriculture especially in developing countries to attain the higher yields, thus there was about 60% of the total release of reactive N with the use and manufacture of N fertilizers. Although there exist higher farm subsidies and lower N fertilizer prices, yet, there is inappropriate fertilization patterns followed for different crops and soil types. There are several reasons for inappropriate fertilizer use. Thereby, there exists huge difference in soil nutrient budgets. Recently, in croplands of developing countries like India, there is built of residual soil P while the residual P build up was reduced in high income countries like Europe due to reduced use of mineral P fertilizer. In case of N, the N deficiency was observed in developing countries while N surplus was observed in developed countries resulting in eutrophication and N_2O emissions. This excessive use of N fertilizer results in considerable N losses through ammonia (NH_3) volatilization and NO_2 leaching. Thus, the nitrogen use efficiency has been as low as ~35%.

In developing country like India, the intensive agriculture, while increasing food production, has caused second generation problems in respect to the nutrient imbalance including greater mining of soil nutrients to the extent of 10 million tonnes every year, depleting soil fertility, deficiencies of secondary and micronutrients, decline of water table and its quality of water, decreasing organic carbon content, and overall deterioration in soil health. An efficient crop nutrient management is important practice and thus, new designer or smart N fertilizers technologies are needed to support the increasing demand and avoid the low nitrogen use efficiency (NUE). The ammonia nitrogen volatilization and nitrate leaching can be reduced or prevented by the use of zeolite carrier material applications which have N in their framework and act as slow/controlled release fertilizers. These materials will reduce ammonia volatilization and nitrate leaching and at the same time increase crop yield. Zeolites are also known for their water holding capacity and in drylands they are the most suitable to prolong moisture levels in severe drought like conditions. In addition to macronutrients, micronutrients can also be introduced into zeolites which can supplement nutrient deficient soils. In India, urea receives significant government subsidy for use in the agricultural sector. Annual consumption of approximately 32 million tonnes has a domestic retail value of approximately US$3 billion. The Indian nitrogen group has reported that only 33% to 35% of urea is used by the plant and the rest is lost due to leaching or evaporation and runoff of soils, resulting in ground water pollution which is a notable environmental issue in the agricultural sector throughout India. Estimates of the economic costs on loss of effective urea utilization rates in India range between US$1.6-billion and US$1.8-billion annually.

23.6.1 As Slow Release Fertilizer

Zhang et al. (2019) studied five mineral amendments in combination, viz., zeolite + rock phosphate (ZP), zeolite + silica calcium soil conditioner (ZC), vermiculite + rock phosphate (VP), and vermiculite + medical stone (VS) and found that these mineral amendments were effective in improving the soil properties in saline areas. Through kinetic experiments,the effect of zeolite application on potassium release in sandy soils amended with municipal compost and found that it resulted in an 18-fold increase in bio-available potassium and reported that there was six times decrease in total potassium leaching. This strongly indicates that in sandy soils and sandy aquifers, there is release of excess nutrients in soil solution and subsequently reduced nutrients movement to groundwater with the use of zeolite (Moraetis et al., 2016). Use of clinoptilolite zeolite along with 75% fertilizer rate to Zea mays (L)on a tropical acidic soil revealed that the nutrient concentration, nutrient uptake, above-ground biomass, agronomic efficiency, and yield were in line with 100% fertilizer application. This suggests that with the use of clinoptilolite, the fertilizer application can be reduced by 25% (Nur Aainaa et al., 2018).

23.6.2 Heavy Metal Remediation

Heavy metals include lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), copper (Cu), mercury (Hg), and nickel (Ni). These enter into soil through industrial activities, land application of fertilizers, animal manures, sewage sludge, pesticides, wastewater irrigation, coal combustion residues, spillage of petrochemicals, atmospheric deposition, etc. They easily enter into food chain pose risks and hazards to humans, livestock, and the ecosystem. Hence, it is very important to protect the soil ecosystem from heavy metal contamination and to restore soil ecosystems contaminated by heavy metals. There are several ways to remediate the heavy metal-contaminated sites such as immobilization, soil washing, and phytoremediation techniques. However, the cost-effectiveness and environment friendliness technology include field applications of zeolites. Zeolites through ion-exchange and adsorption processes, as well as on the surface precipitation/coprecipitation mechanism stabilize or remove the heavy metals in the soil (Table 23.4). Two zeolites—mordenite and clinoptilolite have showed difference in preferantial adsorption of heavy metals and found that at 10^{-5} M of Pb, Cu, Cd, and Zn, and in the presence of 10^{-3} M Ca as a competing cation, the preferential sequence of adsorption was Pb > Cu > Cd > Zn for mordenite, and Pb > Cu > Zn > Cd for clinoptilolite. Even at low-to-medium concentration range (10^{-6} to 10^{-3} M), the zeolites have shown adsorption capacities and removal efficiencies for the two highly toxic heavy metals, viz. Cd and Pb (Yuan et al., 1999). Li et al. (2009) found that zeolite application has raised the pH that caused lead immobilization and also found that the appropriate zeolite dose to significantly reduce soluble lead was ≥10 g/kg. However, the ability to reduce Pb contamination can be enhanced to a greter extent by combined application of natural zeolite and humic acids (Shi et al., 2009). Zeolite is found effective in controlling Cd pollution caused due to use of Cd-contaminated fertilizer leading to soil Cd pollution. Other sources include atmospheric deposition and Cd-contaminated soil amendments, such as manure and sewage sludge. In Switzerland, use of phosphorous fertilizers resulted in 0.49 to 0.57 g Cd $ha^{-1}year^{-1}$in agricultural soils and resulted in 11.3 to 25.6 mg kg^{-1}Cd concentration in Iran. Elboughdiri (2020) revelaed that the capacity of the zeolite for the removal of Pb2+ and Cd^{2+} is directly proportional to the mass of absorbent, initial solution pH, agitation speed, and initial solution concentration. The selectivity sequence for metal ions by clinoptilolite followed the following order: Se > Fe > Cr > Mn > Co > Ni; Na-X: Fe > Se > Cr > Mn > Co > Ni; Na-A: Fe > Mn > Se > Cr > Co > Ni (Flieger et al., 2020). The radii of hydrated ions for Cr^{3+}, Mn^{2+}, Ni^{2+}, Co^{2+}, Fe^{3+} ions are of similar magnitude and equal to: 0.2192 ± 0.0013; 0.2106 ± 0.0022, 0.2061 ± 0.0014; 0.1969 ± 0.0032, 0.2031 ± 0.0019 nm, respectively(Marcus, 1988). The above radii are comparable with the free dimensions of the channels present in zeolites. When both the zeolite and biochar were compared, it was found that zeolite application decreased the bioavailability of Cd, Pb, As, and W, while biochar could immobilize Cd and Pb but mobilized As and W. However, the combination of zeolite + biochar application significantly decreased the

Table 23.4 The extent of heavy metal remediation by zeolites using batch sorption studies

Zeolite used in the study	Conditions	Heavy metal conc	Removal efficiency/ adsorption capacity	Reference
Novel magnetic nano-zeolite (MNZ@MS)	The dosage of MNZ@MS is 1 g l^{-1}, the adsorption temperature is 25 °C	Cu, cd and Pb is a 60 mg l^{-1}, 180 mg l^{-1} and 500 mg l^{-1}, respectively.	The maximum adsorption capacity of cu, cd, and Pb on MNZ@MS is 59.9 mg g^{-1}, 188 0.6 mg g^{-1}, and 909.1 mg g^{-1}, respectively.	Zhang et al. (2020)
Natural Slovak zeolite	5 g of zeolite and 100 mL of Ni solution shaken at a regular rate in a magnetic shaker at 200 rpm	Concentrations of 50, 100, 200, 350, and 500 mg Ni /L	The maximum amount Ni (II) removal (69.51%) was achieved at concentrations of 50 mg/L	Kovacova and Pla (2020)
Faujasite NaY	pH (5–6), adsorbent dosage (0.15 g), 20 ml of solution containing Cd^{2+}, Ni^{2+}, and Co^{2+}	Initial concentration (0.1–10 mmol/ L)	The maximum adsorption capacities (Qmax) were 0.81, 0.85, and 0.92 mmol/g for Cd^{2+}, Ni^{2+}, and Co^{2+} ions, respectively	Araissi et al. (2020)
Iranian natural zeolite (INZ) (Clinoptilolite)	1.5 g (30 g/L) of zeolite were shaken with 50 mL of Pb2+ solutions for 120 min at constant pH 4.5 with 160 times the reciprocating speed of shaker	25, 50, 100, 150, 200, and 250 mg/L Pb2+ solutions	The removal efficiency by INZ has been dramatically reduced from 94.48 to 14.24% with increasing initial Pb2+ concentrations and the most removal efficiency of Pb^{2+} with INZ was obtained at pH 3–5, contact time 15–60 min, adsorbent dosage 20–50 g/L, Pb2+ initial concentration 25 mg/L, and the removal efficiency was increased with decreasing INZ particle size	Moazeni et al. (2020)

bioavailability of Cd, Pb, As, and W by 57.4, 62.7, 56.4, and 22.5%, respectively. Therefore, revealed the combination of amendment (zeolite + biochar) application is best to stable the activate faction of metals (Cd, Pb, As, and W) in soil (Zheng et al., 2020).

Also, if used for manuring, it fastens composting process along with removal of bad odors and aids in improving manurial quality by addressing N losses.

23.7 Economics of Zeolites Application

In terms of economic cost, zeolites are relatively cheap due to their abundance. In markets, the price of zeolite varies depending on their use as detergents, adsorbents, catalysts, and others. However, in general, synthetic zeolites are expensive than natural zeolites. Also, it is known that synthetic zeolites dominate the market with China being the leading producer. The prices of zeolites depend on the application and the treatment received. The recently published report by IMARC Group, titled "Zeolite Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2020-2025," finds that the global zeolite market reached a value of US$ 3.8 Billion in 2019. The zeolite-A synthesized from flyash via NEERI technology was found to have low price (Rs. 18/kg) as compared to commercially available zeolite-A synthesized using conventional raw materials (Biniwale et al., 2001). Depending on the degree of purity of the mineral, the type of phase present, and the treatments received, the price of natural zeolites varies in the market. The price per kilogram can vary between 0.05 and 3.5 USD (Davis and Inoguchi, 2009; Kulprathipanja, 2010). Applications in catalysis can cost between 3.0 and 20.0 USD per kilogram; in the case of applications such as adsorbents, it varies between 5.0 and 9.0 USD per kilogram, and about 2.0 USD for applications such as cation exchangers in detergents.

23.8 Conclusion

Zeolites in combination with fertilizers retain nutrients and therefore increase the soil quality on long-term by enhancing its absorption readiness. It concerns the most important plant nutrients such as nitrogen, phosphorous, potassium, calcium, magnesium, and microelements. Furthermore, pioneer research suggests that zeolite also contributes to sustainable agriculture by preventing the occurrence of environmental problems through increasing N, P, and water use efficiency in agroecosystems.

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Sulfur in Soil: Abiotic Stress Signaling, Transmission and Induced Physiological Responses in Plants

24

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Abstract

Sulfur (S) is the most versatile element among those commonly occurring in plants. It is the reduced S that essentially becomes the moiety for organic residue constituents in biomolecules. The bio-sensitive pathway for S assimilation not only works its demand to cultivate but also for regulation of different metabolic reaction. In plant system starting from cell membrane residues to different signaling compounds, S becomes most important element in maintenance of homeostasis under stress condition. Sulfolipid, sulfoprotein, and other secondary S compounds rank this element to carry messages about enzymatic steps. This is mostly concern with multiple oxidation state of S along with a significant release of free energy which makes the sulfate assimilation more favorable. Therefore, facing abiotic stress with reference to oxidative exposure plants is significantly in debt to S metabolism. This mini chapter is expected to satisfy the S involvement in various corners of cellular and biochemical reactions those let accomplish plant successful stress tolerance.

Keywords

Physiological properties · Reduced thiol · Abscisic acid · Gene regulation · Abiotic stress

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24.1 Introduction

It is the genetic nature of plants to perceive any kind of signaling from abiotic-biotic sources that allows transmitting within the cytosol following gene expression within the cells (Rakshit et al. 2020). Plants are perceived with signals from abiotic stresses like availability of water etc. The signals are manifested into two distinct responses: susceptibility or sensitivity and tolerance or resistance (Saha et al. 2018a). The later is reflected in a broad sense with physiological and phenotypic behavior of affected plants. Water of its universal nature of solvent is most favored with dissolution of almost all nutrients in absorbable forms by the plants within the rhizosphere. Of those nutrients Sulfur (S), an essential macronutrient is functioned with mostly metabolic aspects as well as regulatory processes. Principally, elemental S is attributed as bioresidues mostly with two states: oxidized (S^{2+}) and reduced (S^{-}). Therefore, S is accepted by plant system as a redox carrier. Essential amino acids and their derived metabolites are more important in this aspect which proves these elements not only for nutrient related productivities but also for other facets of responses particularly, under stressful conditions. In fact, a number of cases plant species have markedly documented a wider elasticity in stress responses in different modules (Saha et al. 2018b). Regardless of stressors water deficit/abundance, acquisition of metals, metalloids (may include toxic ones also), excess/inadequate irradiance, anoxic/hypoxic/hyperoxic, fluctuations of temperature are all aligned to one basic cellular status and its deviation. This is precisely oxidative status of the tissues, cellular organelles, and harboring biomolecules within or over the cytosol. An over oxidative redox is the actual fact to be deprived the cellular performances of plants and thereby, its concomitant modulations or effects on overall growth and development. In a more critical way S interacted with biomolecules may also offer different nexus for stress signaling pathways happen to be the most influencing as well as interesting in plant stress episodes. The role of S as element and its introduction in organic residues specifically for abiotic stress have been put forwarded for different corners of plant physiology. From those, the complex nexus specifically balancing the oxidation and reduction reaction cascades to coordinate the primary, secondary, and tertiary responses in abiotic stress tolerance would be quite interesting. In this chapter, a compact discussion is forwarded to understand the established and expected role of S for its interaction, however, at molecular level in perception of stress signaling and responses following tolerance to abiotic stresses.

24.1.1 Sulfur: Its Physico-Chemical Prospects, Molecular Diversity, Plant Biological Entity

S occurs in the native state in considerable amount and also in the form of metal sulfides and metal sulfates. S makes up ~0.04–0.03% of the earth's crust and oceans have S content of ~0.09% in the form of sulfates. It takes the form of a yellow solid naturally and can be found in this state near volcanoes. An atom of S is represented as $^{32}S_{16}$. S contains 16 protons and 16 electrons and its electronic configuration is $1s^2$

Fig. 24.1 S_8 ring

$2s^2$ $2p^6$ $3s^2$ $3p^4$. It has six electrons in its outer shell. So, it can easily accept two electrons in its valence shell to form an octet. S forms polyatomic molecule. Two crystalline forms of S are known: one is rhombic S which is stable at room temperature and the other one is monoclinic S which persists above 96 °C. Both the forms possess S_8 ring (Fig. 24.1). The packing of the rhombic and the monoclinic forms is different. Rhombic form has melting point 113 °C and the monoclinic form melts at 119 °C. Just above the melting point liquid S still maintains the S_8 units but around 150 °C it starts to dissociate successively into S_6, S_4, and S_2. Common oxidation states of S range from −2 to +6. S forms stable compounds with all elements except the noble gases. Some of them are highlighted here: hydrides, oxides, oxyacids, halides, and oxyhalides. The major use of S is in the manufacture of sulfuric acid (H_2SO_4). It is used in the synthesis of other S compounds. It is used in the manufacture of insecticides, gunpowder, fireworks, etc. It is also used in health care (antioxidant, acne problems, anti-allergic, and medication) and in industry and manufactures (cosmetics, rubber industry, fertilizers, etc.).

24.2 Available Forms of Sulfur, Its Variations and Characterization in Agro-Ecological Soil

24.2.1 Inorganic Sulfur Pool and Its Variations in Soil

In general crop species are required the quantitative demand of S as a function of its nature metabolic utilization into nutrient assimilation. Thus, oil seed crops have a greater demand for S than of its other counterparts of element like nitrogen (N) and phosphate (P) (Chahal et al. 2020). For e.g., the variation exists among the cereals, legumes, oil seed to produce equivalent of 1 ton seed within the ranges of 1–5, 5–13, and 5–20 kg, respectively. Moreover, for the oil seed crops in intensive crop rotation the uptake of S is maximum, particularly, when crop residues are extracted from the land with yield. This probes the cause of S deficit in soil and thus alternative S nutrition in the form of fertilizers and amendments is demanded. This is more important for position of S being the fourth essential nutrient in chronological order of N, P, and potassium (K). Thus, the availability of S in different chemical forms/species both ion inorganic and organic versions is well being focused in fertility of soil. Still, S has been paid not an equivalent weight age since long back because soil is richer with fertilizers and atmospheric contribution.

The foremost form of inorganic S in well drained but non-calcareous soil is soluble and absorbable sulfate (SO_4^{-2}) out of oxidation from SO_3^{-2} like reduced forms. This is quite possible in soil with high porosity with drainage in aerobic condition. On the contrary, in lime soil there is ample tendency for SO_4^{-2} in precipitation with Ca^{2+} to from insoluble calcium sulfate. Soil under low pH, aluminum (Al), and iron (Fe) are quite available in exchangeable soil as their corresponding hydroxides, sparingly soluble in soil. About the inorganic counterpart of S, it is in general less copious in agricultural soil as compared to its organic derivatives. However, the most frequent is the SO_4^{-2} radical in abundance with SO_4^{-2} in soil, adsorbed SO_4^{-2} as well as free S as mineral (Siwik-Ziomek et al. 2018). Different basic radicals like calcium (Ca), magnesium (Mg), sodium (Na), zinc (Zn) may complex with S and precipitates in soil as insoluble fractions. Iron would be another good source of S complex, specifically, in saline belt in the form of iron sulfide (Fe_2S), ferredoxin (Fe_2S_2), etc. On hydration with tidal water, it is readily oxidized to SO_4^{-2} and thus acidifies the soil with moderate pH range. SO_4^{-2} adsorbed in the rhizosphere if not up taken by plants instant, it readily percolates into soil to increase the S pool and stored for future use by vegetation. In this physico-chemical process, few basic radicals like Ca and its hydrated residues may facilitate the release of adsorbed SO_4^{-2} in soil causing availability for little of soil surface bound which is possibly limited (Laxmanarayanan et al. 2020). Thus, the combined application of gypsum and limestone becomes more useful in realization of available SO_4^{-2}. The variation of SO_4^{-2} adsorption in surface and sub-soil is due to P residues and other small molecules of organic residues those causing hindrance to soil particle interaction to SO_4^{-2} to occupy the possible sites adsorption. A number of factors are responsible in effect for amount of S in soil solution. Soil SO_4^{-2} in general are not in constant but fluctuate depending upon the input of S from a large number of natural sources like fertilizers and amendments, mineralization of soil S from organic sources, human and animal excreta, natural leaching process, microbial immobilization, etc. (Rathore et al. 2015). Other physico-chemical process encompasses adsorption/de-adsorption, dissolution/precipitation from lesser soluble Al and Fe hydroxide SO_4^{-2} fractions are granted for better resources of S. SO_4^{-2} as anion is more active than nitrate ($NO_3^{\ -}$) and chloride ($Cl^{\ -}$) on adsorption on soil in colloid solution. Still, PO_4^{-2} are ahead of capacity in adsorption over the SO_4^{-2} by its chemical nature and thus use of the former as fertilizer often creates an starvation of S nutrition for plants, especially in poor SO_4^{-2} retentive soil (Naoufal et al. 2018). This is more predominant in grass land soil where SO_4^{-2} concentration varies 3-30 $\mu g.g^{-1}$ according to sorption capacity. However, in clover based grass land this also varies with soil mineralogy, cation exchange capacity (CEC), H^+ concentration, available PO_4^{-2}, adsorption capacity. This is also dependant on depth of soil from surfaces for SO_4^{-2} adsorption and thus in that grassland upon long-term phosphorous pentoxide (P_2O_5) fertilizers with liming there tends to a depletion of S on top than sub-soil. The strong competitive inhibition for adsorption sites of the soil particles exhibited by organic residues as well as PO_4^{-2} anions to replace the SO_4^{-2}. Another constraint is forwarded in such grass land soil where lime practice to neutralize the pH is required as a matter of fact from biological N_2 fixation and NO_3

leaching like physical activities (Nemera et al. 2018). Therefore, S depletion in soil would be caused by SO_4^{-2} desorption from soil surface and thus reduces the absorption by plants. In soil SO_4^{-2} absorption capacity has a great influence on velocity and quantity of S cycling in grazed pastures through regulation of leaching, reducing the unnecessarily uptake by plants, amending S fertilizer competence. A plant successfully adsorbs the SO_4^{-2} when soil could sufficiently adsorb the same into soil solution. The reaction is dependent on low retention capacity that sets free SO_4^{-2} into soil solution in more hastily than soil with high adsorption capacity. On the contrary, high SO_4^{-2} retention in soil is characterised by considerable leaching and significant low desorption. The later may limit the uptake of nutrients by the plants from the soil. Soil moisture, soil porosity like physical properties and low sub-soil pH, availability of basic radicals like Al are the causes of desorption and plant can develop deeper root system to adsorption process (Saha et al. 2020a).

24.2.2 Sulfur in Soil as Organic Residues

It is up to ≥80% of the S in soil may be represented by organic residues through a varied proportion of plants, animal, and microorganism sources. According to the varied depth of soil from top the organic residues distribution S well as its pattern are significantly varied commonly mate with two forms of atom as oxidized state and reduced states. The microbial counterpart is most important to contribute the reduced state of the S with a capricious amount of 1–3% of the dry weight of soil; however, more recently it reaches 3–5% depending upon the humus acquisition of the soil. In the organic residues, the reduced nitrogen in the forms of protein and amino acids as well as some amines predominates from the part of microorganism contribution with C:S ratio between 50:2 and 80:1.5. This is not any consistent proportion, but varies with amount of S input in the soil either from fertilizers or any other soil amendments. In general, the limiting concentration of S is caused by competing the plant up take process and that reaches the C: S ratio in plants within ranges of 80–90, however, excluding the microbial biomass that is the chief source of S turn over. Use of compost or organic fertilizers increases the pool of S from a huge consortium of microbial population, even most of them are non-culturable. As because C, N, H, are the integral element in soil organic matter, the content of organic S is notably allied with soil organic C and N level. In spite of a vast array of organic-S residues there are two important classes like esters of sulfate (C-O-S) and carbon-sulfur (C-S) which are required for plants availability. In addition the concentration of sulfonate (Rai and Singh 2018) and heterocyclic S though lesser in concentration but are common in soil; however, variable in depth. These are analyzed from conventional method of hydriodic acid (HI) digestion and other C-S residues are determined by the subtraction of total organic S from ester S (Prietzel et al. 2007). Very recently this has been more improvised with the techniques like near-edge X-ray-absorption fine structure spectroscopy (NEXAFS) to specify the configuration of S. S being a multivalent anion this NEXAFS also enables the various oxidation states in organic residues in relative proportion. In most conventional methods like HI reduction it accounts almost more than 70% of organic S residues which predominantly represent ester sulfate and sulfamate (C-N-S) being large for the earlier. It is around 45% organic sulfur that is represented by choline sulfate, sulfated polysaccharides, and heterocyclic ring forms like phenolics sulfate by the amount of more than 90 mg kg^{-1}dry soil (Fakhraee et al. 2017). Ester sulfate is the principle transitory form than C-S fraction. This reaches equilibrium earlier than sulfate incorporation into soil, still varies with season and soil texture. It has also been accounted in plants system through up take in a first manner for ester sulfate conversion in soil than other C-S pool. Still, there exist several mechanisms in soil by some physico-chemical reactions where ester sulfate is also in conversion with carbon bonded sulfur but in slow velocity. C-S pool accounts a major account of S containing amino acids like methionine, cysteine directly in proportion to microbial biomass as well as its growth kinetics. There is also good correlation in other soil constituents like N, O, C, P, K with C-S fractions than ester sulfate indicating stability and integrity of the soil, particularly, for humic substances (Saharan et al. 2019). This is out of extensive use in organic manure and amendments than mineral fertilizers in practices to deposit the organic S than ester sulfate. Moreover, the distribution of soil organic S in soil regimes or depth is also varied according to the content of decomposed plants roots and other soil fauna for redistribution. Still, the percentage of HI reducible fraction to C-bonded S may be dependent on climate and soil mineralogy in direct or indirect influence on soil microbial community to adsorb S within soil collection.

24.2.3 Interconversion of Inorganic and Organic Sulfur in Soil: Mineralization and Immobilization

Plant's uptake for S is solely not dependent on desorbed SO_4^{-2} from soil colloids or aggregates but also with mineralization–immobilization of organic residues. In soil there is incessant interconversion or cycling between inorganic and organic S pool in a reversible process. Inorganic SO_4^{-2} is immobilized to organic residues with simultaneous interconversion of organic S as well as mineralization of immobilized S in the forms required for plant uptake. These two process essentially microbial assisted process and the process like biochemical and biological are involved in mineralization of organic residues. In soil with poor fertilizers and atmospheric deposition the release of SO_4^{-2} through mineralization is prime important for crop nutrient requirement. The biochemical mineralization of organic S deals with the hydrolysis with enzymes like sulfatase (sulfo-hydrolase) acted on ester sulfates (Gardner and Senwo 2019). Under depleted concentration of soil inorganic SO_4^{-2} when microbial need S demands is not satisfied, the enzyme hydrolyzing ester sulfate is more active. Even activity is also dependant fully on S application to the microorganism than their requirement in energy content. Application of high dose of SO_4^{-2} causes the enzyme activity more reduced state, whereas a shortfall for the same it would be limiting the activity. In enzyme kinetics the activity of the sulfatase is regulated by feedback inhibition with inorganic SO_4^{-2} concentration in soil. The improved mineralization outcomes the induction of sulfatase activity which arises from the reduction of SO_4^{-2} levels in soil. Importantly, the biological turnover of S occurs at the time that microorganisms use C bound sulfur both for carbon source with byproduct of SO_4^{-2} as released. This exclusively means the S mineralization occurs as a simultaneous event as use of S for energy requirement by the microorganisms (Sahu et al. 2018). The acquisition of S is proportionately used both for cell material synthesis and only the left over above the requirement for plant growth. This is one of the evidences that carbon bound S undergoes mineralized as a tie between microbial metabolism and rate formation of organic carbon bound S. In comparative approach for carbon bound S and ester S, the former is more ahead of turn over or mineralization to maintain S flux in soil. This is more prevalent in short-term cycling where ester bound S form is less accessed to be mineralized as because of bond rigidity between C and S in humic biomass (Piccolo et al. 2019). Plant nutrition is supported by S nutrition through sequential oxidation of C bound S into esters. From the role of crops, S mineralization appears to be physiological perspective of plants. A hasty mineralization of S occurs under the promoted condition of solubilization of SO_4^{-2} into the plant mass residues and also hydrolysis of organic S containing matter at the end of crop period facilitating abscission or senescence (Samanta et al. 2020). A higher up of soil pH by liming is occasionally used to accelerate the microbial commotion in soil. Liming with chemical like calcium carbonate may raise the pH in soil and possible intensify of mineralization may be due to synthesis of peptide bonds of organic substances. The compounds like Fe and Al hydroxy sulfates become more soluble and hasten in mineralization process under higher pH of liming process. From the other aspects the soil characteristics like temperature also higher up the mineralization due to optimization of enzymes activity in soil microflora (Prashar and Shah 2016). Microorganism may contribute the released SO_4^{-2}. A simultaneous operation of mineralization as well as immobilization is important for cell constituents in plants through growth and development. So, rate of mineralization ought to be granted for the application and management of S fertilizers in soil in exact doses. Moreover, immobilization of S would also meet with several factors including soil physico-chemical properties, S fertilizers and organic amendments, weather specific S deposition in soil, etc. as well as types of crops used. As for e.g., application of reducing sugars, leaf dust may increase the immobilization of SO_4^{-2} depending on C:S in those amendments (Yang et al. 2019). The C:S is more important with a critical values with mineralization and immobilization occurring at above or below, respectively. Notwithstanding a general rule, however, sole carbon source from organic matter or any metabolized byproduct determines the amount of SO_4^{-2} leads to immobilization process.

Now, immobilization of SO_4^{-2} is a precise process that is governed by sufficient accessibility of organic C and N in soil for transformation of ester sulfates. Still, ester sulfates are more accessible to incorporate SO_4^{-2} than that of C-S bonded compounds which is more aligned to microbial activity. Plant rhizoids and microbes release specific enzymes like sulfo-transferases those are readily available for ester sulfate synthesis. This also varies with the soil depth where SO_4^{-2} incorporation into those is indirectly related to reduce microbial activity by release of enzymes like sulfo-transferase (Heinken and Thiele 2015). S as biomass carries minimum in amount (≤ 3%) of the total S in soil, still, it is the governing factor in controlling S transformation and due to its labile nature also contributes in S cycle. Undoubtedly, the greater amount of potentiality availability of S in higher plants directly depends upon the S in biomass. The soil characterized with low amount of inorganic SO_4^{-2} is also varied with inadequate soil microorganism biomass. Inconsistency of microbial biomass S may link amount of inorganic SO_4^{-2} in soil and it reports availability of substrate influence microbial activity. The appliance of carbon source would be a determinant to induce the microbial activities, however, varies with wider ranges in soil types. Thus, biomass with 0.9–2.6% of total organic S might be allied to bio-mass C (Nanda et al. 2016). A wider array of carbon sources covering cellulose (Mohammadkazemi et al. 2015), municipal waste (Dürre and Eikmanns 2015), domestic sewages (Liu et al. 2018), composed and farm yard manure (Noirot-Cosson et al. 2016) are more crucial to modulate the mineralization of SO_4^{-2} and its concomitant ester and C bound S residues. The C:S in microbial biomass differs 30–149 and of course significantly negligible than C:S of total soil biomass. The types of amendments and its total S content would appreciably control the proportion of released SO_4^{-2} in soil for downstream utilization in immobilization of organic residues for crop growth (Ahmad et al. 2007). The ratio of C to S immobilization in soil is 400:1 as referred earlier. Due to nature of S in soil predominantly as organic, the cycling of available and unavailable forms is pursued less significant in mineralization–immobilization process of organic forms. Under condition of water logging with extended period the sulfate reduced to sulfide (Pollman et al. 2017). The later is convenient in soluble form by precipitation and that facilitates the removal of S from the S availability pool. This happens to be essential for acquisition of S supplementation in soil for plants' nutrition in principle of major nutrients ratio.

24.3 Sulfur Supplementation Through Carrier System in Soil for Plants' Nutrient Inputs

Total fertilizers production and its industrialization have become sluggish in last few years all over the world. Still, the demand is predictable to have scale up with the customized synthesis for quality and quantity of economical gypsum as byproduct. Categorically fertilizer inputs from sulfur are rested on two broad categories as inorganic as well as organic products. Undeniably, in those two categories sulfur must be granted as primary nutrient and with other accessory elements also S may be the most contributory. Gypsum would be a readily example where lesser in proportion of S (18%) may also be granted as prime important than next element like calcium (23%) for sensitivity in plant growth. It is in regular practice to use gypsum as a good source of Ca for few crops like under pulses as well as to nullify the solidity and acidity of the soil (Rashmi et al. 2018). Besides to supplement as an essential element, S has its intrinsic property to include as fertilizer for lowering the pH of the loamy alkaline soil. While sulfuric acid is neutralized, gypsum is recovered from the uses of byproducts of lactic acid, titanium di oxide, phosphadic fertilizers. Inorganic fertilizers as thiosulfate, mostly ammonium thiosulfate where both sulfur (26%) and nitrogen (12%) are present that has a good command on crop growth. For applications in irrigated water and with other recommended fertilizers like urea, aqua ammonia, ammonium nitrate, N, phosphorus etc, still, gypsum is well customized in crop practices (Qayyum et al. 2017). In few cases S may also be granted as secondary interest in plants nutrient availability notwithstanding of its considerable quantity. The gypsum and calcium phosphate [Ca $H_2PO_4)_2$] mixture in single super phosphate would be an example in which about 9% of phosphorus content is accompanied by 11–12%of S also. Likewise, $(NH_4)_2SO_4$ is another form where also S content is substantially high (21.2%). Potassium sulfate (K_2SO_4) with magnesium sulfate ($K_2SO_4{\cdot}2MgSO_4$) contain essentially maximum content of elementary sulfur as 18.4 and 22%, respectively (Dick et al. 2008). It holds true that fertilizers having high analysis of N, P, and K contain essentially low input of elementary S. Exercise of triple super phosphate containing 23% of P as a substitute of single super phosphate is less in potential for plants' nutrition since the former contains less (3%) than the later as well as in low rate of application also. Ammonium nitrate (NH_4NO_3) though contains higher values for N but no S, thus it is hardly recommended for soil in field depleted in S concentration. Moreover, S deficiency may be expected in long-term application and practice in acid soil also (Eriksen 2009).

In India S deficiency records about 40–45% of across the country where available forms below the critical ranges cause the reduction in yield in crops, particularly, oil seed pants. Mostly, S free fertilizers, high yielding cultivars, natural S oxidation, regulation of industrial pollution as emerge of sulfur dioxide (SO_2), soil leaching, rain fall area soil erosion, intensive cropping system, non-use of organic manure are the most possible clues for S deficiency (Meena et al. 2013). So both for enhancement of use of S efficiency and reduction of S deficiency, improved S fertilizers are implemented. S in organic/animal manure is generally overlooked in agricultural system. However, economically composts, bio-solids covering types of organic manures are more important in S supplementation for oil seed crops. Land preparation with such manures are standardized from best results on initial and subsequent crop growth stages, however, not any conciliation with other nutrient content replaced by S. The byproducts of chemical factories may also serve better S supplementation as a potential source of fertilizers. Admitted well that S in gaseous states is a potential air contaminant and generally not supported with any of its beneficial effects. With example $(NH_4)_2SO_4$ is a byproduct of metallurgical coke for coke oven gases. Flue gas is another alternative source where ammonia (NH_3) as sorbent is reacted with SO_2 gas. From the coal gasification plants, it is also possible to produce fertilizer quality of $(NH_4)_2SO_4$ but not widely accepted for expensiveness. The fossil fuel may be another good alternative for large amount of S in the form of SO_2. Understanding the toxicity of SO_2 the improved technique employs special devices where a huge amount of calcium sulfite ($CaSO_3$) and calcium sulfate ($CaSO_4$) are the byproduct on Ca based sorbent to react with SO_2. In more advanced forms sorbent used in the other formulations like $CaCO_3$, dolomite [$CaMg(CO_3)_2$], and calcium hydroxide [$Ca(OH)_2$] also may produce better resolved compound for

$(NH_4)_2SO_4$. In this way epsomite ($MgSO_4$, $7H_2O$) production is more potential in release of Sr and application feasibility than gypsum also (Moyo et al. 2019). Desulfurization of flue (FGD) gas is commercially based on two broad categories like wet and dry processes. In the earlier the case the FGD produces exclusively wet waste or byproduct, whereas the later refers a mixture of both wet and dry powder as product (Wang et al. 2019). A mixture of calcium sulfite and gypsum is the principle component of the wet form and is characterized by moderate cause of soil toxicity after application. However, the toxicity undergoes revised with a readily oxidation of calcium sulfite to calcium bisulfate or gypsum categories of compounds. In another process of oxidation with oxygen under pressure the calcium sulfite along with gypsum is converted into calcium sulfate, a restively pure form of gypsum that is more frequent in stable S fertilizers.

S as element has a good potential for being a potential fertilizer also, however, in a process of biological reactions in the plants. It is the oxidized state that regardless of crop species can absorb before it is metabolized in the tissues following its conversion into most reduced states of amino acids (Sperringer et al. 2017). Still, oxidation of reduced forms of S in soil may be categorized as chemical or biological or a combination of both under exclusively aerobic condition. Likewise, in soil diverse groups of S oxidizing bacteria are found in full or partial capacity of utilization of many reduced S compounds (Pokorna and Zabranska 2015). These bacterial groups include autotrophic like *Thiobacillus* are given more significance in as soil microflora to enrich rhizosphere with most amenable forms of S for absorption. In the soil S oxidation regardless of auto/heterotrophs pursues the following S oxidation by chemical process with various redox states of moieties:

$$S^{2-} \rightarrow S^0 \rightarrow \left[S_2O_3{}^{2-}\right] \rightarrow \left[S_4O_6{}^{2-}\right] \rightarrow SO_3{}^{2-} \rightarrow SO_4{}^{2-}$$

In acidic soil S nutrition is quite acquiescent to crops by few ways predominantly those cover oxidation of sulfide moieties, elemental S is mineralized into sulfuric acid, formation of other mineral phase from dissolution products (Fanning et al. 2002). Acid S ($SO_4{}^{2-}$) soil in agricultural field is the common problem throughout the world out of anthropogenic activities. Formation of sulfide-S is another constraint for nutrition in crops where available S is converted into other compounds like pyrite. This is chiefly available in soil water interfaces like submerged or waterlogged paddy field in a reaction like: $Fe^{+2} + S^{-2} \rightarrow FeS$, $FeS + S^0 \rightarrow FeS_2$ (pyrite).

Soil temperature also affects the reactions for generation of such FeS compounds under anaerobic condition. Soil containing elemental S may also undergo autooxidation to yield thiosulfate (S_2O_3) and tetrathionate (S_4O_6). These oxidation reactions are also dependant on the decreased soil particle sizes in an inverse correlation in acidic pH (Ettler et al. 2015). The microbial metabolic activities could influence the soil temperature that induces sulfur oxidation to pyrites like compounds. More so, S undergoes oxidation when soil moisture is overlapped or equilibrated nearly with total water holding capacity or field capacity of the particular soil (Zhao et al. 2015). However, S nutrition in more improved version of formulation may control or limit the oxidation process of S by introduction of autotrophic bacterial species like *Thiobacillus*.

24.3.1 Improved and New Formulation of Sulfur Supplementation

In overcome of the oxidation processes those links acquisition of the more sulfides residues in soil to deteriorate the soil fertility more improvement or attention have already been in success. This is based on to escalate the S use efficiency as well as to prevail over its deficiency in plant and soil, respectively, through some new formulation. The application of such formulated or modified fertilizers may have the downstream effects on application including reduction of nutrient loss, slow but regulated release of nutrient to rhizosphere, lesser vaporization of nutrient under ambient soil temperature, reduced nutrient leaching, improved water holding capacities, moderate chemical transformation, etc. (Lodge 2017). This conceives the concept for nano-fertilizers formulation as with nano-material essentially with any compounds, elements, radicals within molecular particle sizes of 100 nm. There are naturally occurring non-particles those had quite been in use for agriculture purposes with common citation of zeolite elements. Still, engineered nano-particles have also been selective usages in crop science with regard to nano-fertilizers concept. These would be granted as new formulations in fertilizers based agro chemicals where S would be the prime selections in various S based agro chemicals (Manjunatha et al. 2016). Technically, three possible outlines are most in use like in powder, solutes, and paste where S as element is transformed into nano forms. In more recent studies technological advances have presented a surface modified zeolite with nano structure that eventually releases S in moderated or in slow rate (Ma et al. 2016). In recent investigation zeolite has proved as a good adsorbent for S nutrition in addition to higher CEC as well as slow release fertilizers mostly for slow release NH_4 ions. A significant down regulation of $SO4^{-2}$ release has been the properties for such surface modified zeolites and that also raised the possibility for use in purpose of slow release fertilizers. The minimum sized particles of S within the nano ranges has also aspired the better fungicidal properties than of its corresponding bulk molecules and thus such a particle would be more useful in support of unwanted environmental effects on nutrition. In a similar way, nano zeolite based slow released nitrogen fertilizers could quench the nitrogen after a long period than urea as conventional fertilizers. NH_4SO_4 is the primary S releasing nitrogen fertilizers. Conventional S fertilizers can release S after a short while on application in soil to release the rhizosphere. However, the disadvantage is maximum rate of S released over a shortest period of time in soil solution and that expedites the leaching and volatilization related loss before it reaches to the rhizosphere (Vinod 2015). Therefore, an outstanding carrier system of S fertilizers must come in question for minimum loss due to weathering. Therefore, a nano zeolite with S coated surface and conventional NH_4SO_4 fertilizers would be most important issues in any new formulation of S nutrition.

24.4 Translocation of Sulfur Through Cellular and Non-cellular Paths in Plant

S with its abundant solubility particularly, in the form of sulfate has a greater movement through the xylem sap. As compared to nitrate and phosphate the mobility of sulfate is not any hindrance to the major plant metabolite flask. The S portioning in the different bioresidues as well as its distribution in different organelles is significantly variable as compared to nitrate and phosphate (Ajala and Alexander 2020). Specific channel proteins and few transporters for S have been cloned from roots of different plant species. In most of the cases, sulfate transporter (SULTR) falls with its distinct features in specific plant growth. Under stressful condition the expression of SULTRs and their functioning are much not extensively studied. According to tissue specificity SULTR1 is more expressed in roots, whereas few low affinity transporters are responsible for loading and unloading into conducting tissues. Few groups (SULTR3) are more expressed on plastid membrane. Tonoplast bound proteins are included with few SULTRs to load-reload into vacuoles for S. For the drought stress SULTR3, a plastidial transporter is also functional in few species on their roots. The interaction of other stress responsive moieties like abscisic acid (ABA) may alter the expression of SULTR and cysteine biosynthesis. Undoubtedly, cysteine besides its antioxidation functionales also denotes of S to the molybdenum co-factor. The later in its sulfurylated form facilities the penultimate steps of abscisic acid (ABA) biosynthesis (Ghasemzadeh et al. 2019). In many reports there exist a synergistic or eventually exclusive dependence of S metabolism to ABA biosynthesis in plants. This might be the reaction in most of the abiotic stress tolerance species. In most of the abiotic stress tolerance plants are over expressed with few sulfurylated along with ABA overexpression (Saha et al. 2019). As for example under drought stress in *Arabidopsis* *At*SULTR3:4 is simultaneously with *At*SULTR3:1 in roots. In mutation with ABA related genes for low level of concentration could impair sulfate assimilation under drought stress.

24.4.1 Flux of Sulfur Through Vascular System and Its Utilization Under Abiotic Stress Imposition

There is no doubt about the over expressed concentration of sulfate under stressful condition as good as other radicals like nitrate, phosphate, etc. Sulfate is also behaved as one of the signaling compound, perhaps through its duel redox nature: reduced and oxidative states. Therefore, utilization of sulfate must be required in many stress responsive residues in plant system particularly, which may communicate root to shoot signaling (Safari et al. 2019). Likewise, water stress as a function of stomatal opening and closure may also meet for one of its perception molecules as ABA. ABA has well-being in molecular regulation with active S metabolism in plants. Conventionally ABA biosynthesis is localized more in leaves particularly, in early water stress where cysteine biosynthesis would be a factor for S involvement.

The effect of ABA on cysteine biosynthesis is also indirectly related for ABA and vis-à-vis (Cochetel et al. 2020). Even the ABA related elements (ABREs) are also substituted to take part on cysteine biosynthesis regulation with dehydration response element (DRE). Therefore, the intimacy of S assimilation with ABA functioning may take another facets of S metabolism in plants (Rajab et al. 2019).

24.4.2 Interaction of Plant Growth Regulators Under Stress with Sulfate Accumulation in Soil

Plant growth regulators are essentially subjected to be moderated by any of the nutrients in soil and its concomitant acquisition in plant body. Sulfate reduction in plant tissues through various intermediate residues has intimate associations with growth substances. These are mostly based on S containing amino acids like cysteine, methionine etc to supplement few growth regulators like ethylene, brassinosteroids etc. Of those reactants ABA would be more lenient in connection of stress episodes with special reference to dehydration and dehydration induced other environmental extremities (Saha et al. 2020b). ABA, a 15-C sesquiterpene acts as plant growth regulators. The site of synthesis is the chloroplast from normal carotenoids biosynthesis following mevalonic acid pathway (Zhao et al. 2019). In its biosynthesis zeaxanthin and immediate precursor converted into violaxanthin by epoxidation reactions. The involved enzyme zeaxanthin epoxidase is overexpressed in plastids when plants are induced to S accumulation.. A 15C product xanthoxal with its antioxidation converted into ABA preceding abscisic aldehyde. ABA aldehyde oxidase is another part where sulfate accumulation would be a significant determinant to modulate the water stress by ABA mediated hydroactive stomatal regulation. Therefore, sulfate accumulation may be integrally associated with stress responses where ABA involvement would be complementary to impart possible tolerance. This also confirms that the ABA biosynthesis is not only related to the water stress related phenomenon but also to the mineral nutrition which sometimes becomes a factor for induced dehydration (Saha et al. 2020c). In addition SULTR3 is expressed in leaves more focused to transport of sulfate into chloroplast. In mutant species of *Arabidopsis* the absence of these transporters is coupled with the reduced transport of sulfate into chloroplast and thereby the concentration of ABA is also inadequate. This undoubtedly indicated that the linearity of ABA biosynthesis along with S metabolism is complementary for plant growth. Cystine in its biosynthetic pathway in cytosol is developed from cysteine O-acetylserine residue and the enzyme serine acetyltransferase (SAT) is highly expressed in cellular organelle particularly, mitochondria. In C_3 plants SAT is linked to phosphoglycolate metabolism. The released sulfide is resynthesized in non-green plastid by sulfate reduction (Pinnell and Turner 2019). Therefore, sulfide also plays roles in cysteine biosynthesis. The later indirectly is complemented with ABA biosynthesis for its induction and regulation. So, sulfide from sulfate reduction can gear up the cysteine biosynthesis. The later can provide the S to activate the molybdenum co-factor (Moco) reforming the S-Moco. Alternatively, ABA aldehyde oxidase (AAO) could use the active S-Moco to catalyze the penultimate steps of ABA biosynthesis in chloroplast (Balusamy et al. 2019). There recorded the recruitment of more S atoms from an unidentified donor residue called metal containing pterin (MPT). The later may have the access to be a direct precursor of Moco with special condition of dehydration (either by salinity, excess evaporation, irradiation, etc.). The ABA biosynthesis is overexpressed with two predominant rate limiting enzymes: zebularine (ZEB) and 9-cis-epoxycarotenoid dioxygenase (NCED). S could be a factor that its deficiency can alter the expression pattern of the NCED as well as ABA3. These genes are also responsible for Moco biosynthesis. An expression of NCED under dehydration response promoter of *rd29A* in *Petunia* can improve the resistance under drought condition. Therefore, AAO and Moco are highlighted for their involvement with S metabolism under ABA involved pathway against drought stress (Xu et al. 2019). This has also been illustrated when gene silencing with SULTR3 can downregulate the ABA concentration in leaves even under S depleted soil. This is a clear indication that the plant genotypes with efficient S metabolism could able to sustain the abiotic stressors which is directly related to dehydration phenomenon.

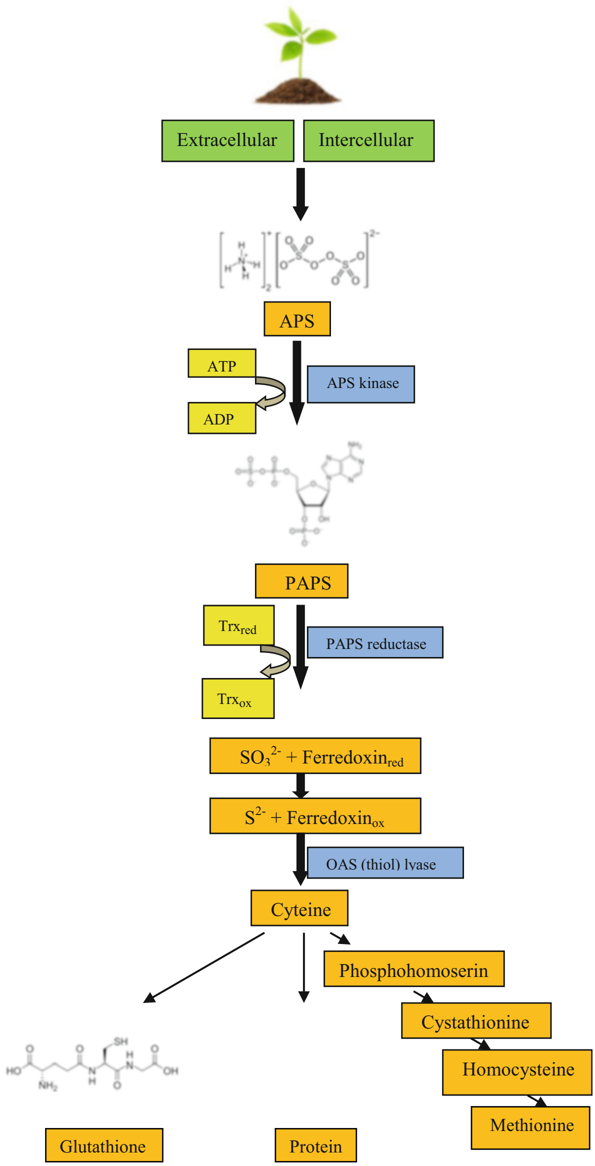
24.4.3 Sulfur in Signal Perception and Transduction Pathways Under Drought Stress

It is the xylem sap when drought stress is initially perceived with a change in water relation through tension (a negative pressure xylem conducts) and osmotic pressure of the phloem tissues. Sulfate unlike other macronutrients could have a better ability to increase the concentration through xylem sap. This may be an indicative of the fact that partitioning of S is different from that of nitrate and phosphate. Beside this, higher sulfate insists its possibility to response during drought and other stressors inducing the water deficit like ABA through xylem ducts. It is the sulfate that causes stomatal regulation. This is more accurate when early stages of water stress are set, the ABA biosynthesis is a relief in leaves. This is accompanied by an elevated concentration of cysteine when ABA was treated. Therefore, the reciprocal relationship is the feature for signaling nature of S. This is more established with a regulation of O-acetylserine (thiol) lyase by ABA. In typical ABA deficit mutant where dehydration response element in substitute of S assimilation is not observed in abundance (Fang et al. 2019). With the all-around role of ABA facing the stress a significant regulation mechanism for mineral nutrition with reference to S was initially reported (Zhang et al. 2019). The signaling molecule and its activity are in actual interplay with a number of other residues within cytosol. This constitutes a signal cascades mechanism that essentially related to up and down regulation of several genes those are significantly modulating for the rate limiting enzymes. Likewise, the biosynthesis of ABA from zeaxanthin is followed by epoxidation. Zeaxanthin epoxidase is the enzyme that converts zeaxanthin into violaxanthin. In plastid, violaxanthin is converted into its isoforms 9′-cis-neoxanthin. This step is more important for the growth regulation in overall of the plants. Neoxanthin is cleaved to form 15C zanthol, the enzyme NCED is the rate limiting enzyme and has been cloned from different plant species. For inhibition of seed germination shoot and root growth in inverse manner, inducing abscission following senescence and other degenerative metabolisms are accelerated by zanthol. The later is catalyzed by amino acid oxidase (AAO). The application of S is most attributed to activate both NCED and AAO for over accumulation of ABA (Lu et al. 2020). Undoubtedly, ABA happens to be the most emergent growth regulator in relieving the stress in many ways. Therefore, S application must be interplayed with S metabolism (Hao et al. 2019). As, for example, on dehydration stress in maize mutant a number of recessive genes (*vp2*, *vp5*, *vp7*, *vp9*) could block the biosynthesis of carotenoids following its effect in lower concentration of ABA which is also reciprocated by application of S in soil. This may confirm that ABA biosynthesis through carotenoids pathway is also dependent on nutrient status of plant like S.

24.5 Sulfur Residues in Plants: Antioxidation Pathways Through Non-enzymatic Mode

A number of phytohormones have their common residues either direct or indirect made as major constituents. Those phytohormones are significantly required S or any of its derivatives in their biosynthesis. The different plant bioresidues are involved in S assimilation (Fig. 24.2). The most common example is cited with ethylene which depends on the biodiversity of S by S containing derivatives S-adenosylmethionine or SAM which is rapidly converted to 1-aminocyclopropane carboxylic acid or ACC. ACC is the immediate precursor of ethylene biosynthesis (Vanderstraeten et al. 2019). On these conversions the byproduct 5′-methylthioadenosine comes back to methionine and increases the S pool in the cytoplasm. There are many derivatives of S (Table 24.1). Cysteine and cysteine are inter-convertible residues and happen to be another source for S pool in plants (Gahl et al. 1982). As already mentioned earlier, S deficiency along with ABA biosynthesis may also hindered SAM accumulation. Therefore, S undoubtedly would be a key factor for both ABA and cystine residues, as required for water and oxidative stress tolerant, respectively, regardless of plants. Other phytohormones like auxin groups are with urgent requirement for S metabolism. This is more observed in rice seedlings where inadequate S metabolism leading to decrease in cysteine may corroborate the auxin dependent growth in roots (Jia et al. 2015). In fact, cytokinin though not directly related to S incorporation in its biosynthesis, still, cytokinin receptors on plasma membrane are impaired in perception with S deprivation. It is the S^{2-} that directly incorporates into cysteine-methionine-SAM. This is coordinated in contribution of stress responses by a series of residues like phytohormones (gibberellic acids, auxin, cytokinin, salicylic acid etc.) (Banerjee et al. 2018). In addition the most active intermediate O-acetylserine happens to be a precursor of cytokinin which realized on less identified complex interacting with serine acetyltransferase. The reaction is required also for activation of jasmonic acid (JA) signaling pathway. In this pathway expected those less identified compounds are 12-oxophytodienoic acid (OPDA). This compound is

Fig. 24.2 Plants bioresidues involved in S assimilation



essentially required on plant cellular membrane where JA biosynthesis is required. Ethylene production may be sharing with exclusive metabolites in S metabolism. When salt stress is relieved by sulfate application a similar up regulation of ammonium persulfate (APS) reductase activity is mutually exclusive with ACC. On the other hand, methionine biosynthesis also linked to ethylene and S by a common residue SAM and SAM is the penultimate ancestor of ethylene. In mustard, ethylene may stimulate the ATP-sulfurylase or ATPS activity for S uptake when ethylene

Table 24.1 Some of the sulfur derivatives and their physiological properties

Sulfur derivatives	Chemical formula	Molar mass	Solubility	Appearance
Glutathione (GSH)	$C_{10}H_{17}N_3O_6S$	307.32 g. mol^{-1}	Water soluble	Colorless, transparent, thin cylindrical in shape.
Methionine (met)	$C_5H_{11}NO_2S$	149.21 g. mol^{-1}	Water soluble	White crystalline powder
Hydrogen sulfide	H_2S	34.08 g. mol^{-1}	Water soluble	Colorless gas
Cysteine (Cys)	$C_3H_7NO_2S$	121.15 g. mol^{-1}	Water soluble	White crystals or powder
Allicin	$C_6H_{10}OS_2$	162.26 g. mol^{-1}	Soluble in organic solvent	Colorless liquid

concentration is over produced (Asgher et al. 2014). SA is another moiety which along with S assimilation modulates the plant stress responses. Plants under SA treatment could contribute more reduced glutathione as a result of glutathione reductase activity. SA, the common phenolics dominates S metabolism by increased cysteine and S contain through ATPS activity. A stable maintenance of cellular redox is done by a sulfation reaction with the enzyme sulfo-transferase or SULT. It is quite known about the SA signaling. It is predominantly the reaction of S nitrosylation where the activated SA is produced requiring glutathione for activity. Therefore, SA and S metabolisms are also complemented to each other for overall plant stress tolerance. The increase in acute phase response or APR transcript under salinity is down regulated in gibberellic acid signaling mutants of maize. It is interesting to note that the gibberellic acid metabolizing enzyme remain inactivated. Therefore, gibberellic acid signaling may not be post-translational level rather post-transcriptional level. Oxidative stress, a common platform regardless of any stressors is related to be relieved by both gibberellic acid and S application. In physiological level the study reveals the S use efficiency through over accumulation of glutathione under heavy metal stress is a quite demand regardless of plant species.

24.5.1 Crosstalk with Sulfur and Nitrogen Reacting Species

Reactive nitrogen species (RNS) are the molecules or some species of molecules which include nitric oxide (NO), superoxide ($O_2^{\cdot -}$) as produced by inducible activity of NO synthase and nicotinamide adenine dinucleotide phosphate oxidase or NADPH oxidase, respectively (Luis et al. 2006). Originally NO is regarded simply as environmental contaminants for NO complex (nitrogen dioxide or NO_2, NO, etc.) mostly as an outcome of industrial and fuel combustion. RNS becomes more vulnerable when combine with reactive oxygen species (ROS) to show its more detrimental effects of tissues. Collectively this is called nitrosative stress. Free radical as NO is behaved as a residue which has the ability predominantly as a chemical messenger. It has been reported since back that RNS covers a diverse physiological and cellular function particularly, under stressful condition. NO is the preliminary compound which accompanied related molecules called RNS. In plant metabolism the most common of those includes peroxynitrile or S-nitrosothiol. The later is more convenient to be produced from S metabolism with occasional introduction of NO. Collectively these molecules called conjugate or oxidized an array of biomolecules. Those functions as transporter for NO and thus the signaling approach in plants for root morphogenesis to stomatal regulations is induced. The nitration and nitrosilation are the most important events in plant signalling paths which in downstream regulate many cellular vis-à-vis physiological activities in plants. Besides the signaling nature, NO is involved in the abiotic stress tolerance with reference to oxidative stress. This is more accurate with few steps in Halliwell-Asada pathway where replenishment of glutathione is most important. On the other side, S application could also induce the ratio of reduced and oxidized glutathione (GSH:GSSG) in roots through an increased S absorption (Liang et al. 2016). This undoubtedly is the fact that S and NO would be synergistic in action and more accurately is in the involvement in the induction of S absorption, translocation path to incorporate the S into reduced glutathione (GSH). Therefore, abiotic stress tolerance in plants would be obliquely modulated with different genes concerning the cellular redox and with involvement with NO. The ascorbate glutathione pathway for enzymatic/non-enzymatic antioxidation would be required in NO either to perceive the signal or to supplement S into non-protein thiol. This has more been clarified with plant species where s-nitrosoglutathione (GSNO) is behaved as storage residues to release NO. Therefore, NO could directly be synthesized from nitrate reduction pathways or a transient storage product (GSNO) in limiting stress. The S-nitrosoglutathione reductase in its pathway releases NO and NH_3. The later would supplement nitrogen metabolism where any possibility for NO generation is open (Kirisci and Kamalak 2019). So, ROS and RNS may have the synergistic action with stress tolerance through the GSNO pool. Hydrogen sulfide (H_2S) is apparently a toxic or pollutant to plant tissue but when exist through NO synthesis pathway, it becomes an important signaling residue. Sodium hydrosulfide (NaHS) reported as an H_2S donor to late stressed oil yielding plant (*Sesamum* sp.) where increased NO content is accompanied with H_2S accumulation and that together up regulate the tolerance (Shivaraj et al. 2020). Sodium nitroprusside (SNP) is another motivator of H_2S production where NO would be the result in over accumulation (Singh et al. 2020). Therefore, it is the dual effect of signaling by both NO and H_2S where plants ultimately benefited with tolerance.

24.5.2 Nutrient Diversity and Sulfur for Stress Tolerance

S plays a key role in plant growth and development in different aspects (Fig. 24.3). S being an electronegative element possesses a unique opportunity to synthesis of compound containing N, P, K, Mg, and selenium (Se), etc. It is the oxidized form of selenium which is in competitive mode for absorption of K, molybdenum (Mo), and zinc (Zn). The sulfate is the common storage in the cell cavity which is translocated out of membranes and put into xylem sap against potassium ion or K^+. Se is another competitor for transporter in cell membrane against S and thereby, Se may copycat the requirement of S uptake. Se has another important criterion to induce specific sulfate transporter when sulfate is itself absent. In plant system the most common polyamines (PAs) with di, tri, and tetra amines are represented by putrescine, spermidine, and spermine. S has its catalytic involvement in their biosynthetic pathway in a particular residue, called SAM. The most over expressed enzyme of its biosynthesis SAM decarboxylase is also induced by sulfate supplementation. The release intermediate in this reaction behaves as a donor of aminopropyl subunit for spermidine and spermine biosynthesis (Sekula and Dauter 2019). So, the parallel trend for S deficiency to PA metabolism becomes trait for stressed plants. In few cases PA with its cationic animated residue may support as compatible solutes in osmoregulation when the plants are induced with S. Therefore, from the above discussion, S the nutrient with its variable chemical valances is also most diverged for its biological properties. It is the signal perception to start with by the role of S following maintaining of bioresidues cytoskeleton and redox homeostasis is covered by S. Besides, in maintenance of adequate reductive redox for the biological active compounds, S has intimate association with nutrient also. The conjugation with different metabolites of S also extent its promotive effect in induced tolerance for plants. Categorically, antioxidation strategies with non-thiol compounds and biosynthetic path have been well exercised in different plant species with improved antioxidation. More research is awaited and still to be informed the other accessory

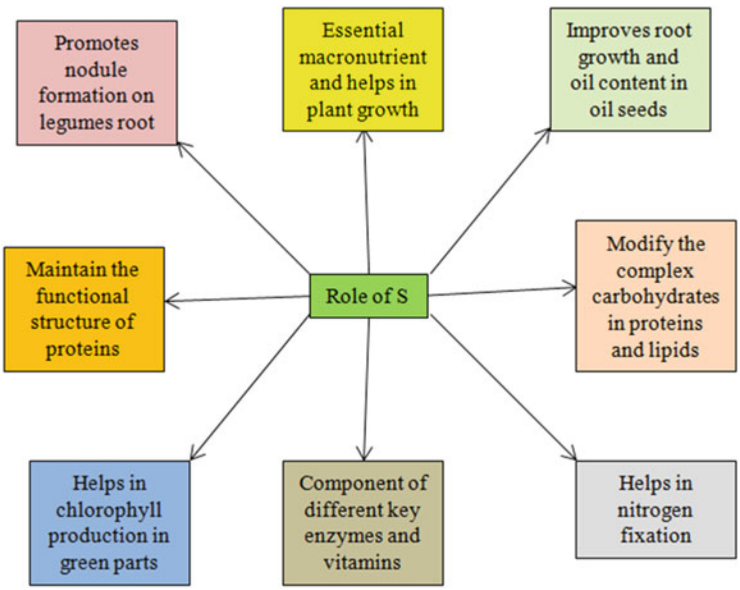


Fig. 24.3 Roles of S in plant growth and development

paths of S metabolism in quest of tolerance species against multi-facets environmental stress.

24.6 Conclusion and Further Scopes for Research

This chapter aims to make a comprehensive study for S status in soil as well as crops with regard to its availability, utilization, specific requirements, regulation, and management for sustainable resources. S being a macroelement has already been deserted for its magnitude in soil fertility for crop withstanding as unlike other elements like N, P, K, etc. Advances in research have de-folded the basic mechanism in physiological utilization of conventional S fertilizers and its more modified version as nano-fertilizers. The chemical formulation and its relevance have more established for sustainable as well as enhanced crop yield and depletion of from soil out of harvested crop biomass and grain, retarded atmospheric contribution, concentrated fertilizers with absolutely nil or significantly reduced sulfur as by-products. Under the circumstances of changes in agricultural perspective specific research, however, not exhaustive needs to be crucial in proper utilization of sulfur and its consequent manifestation of crop improvement. Soil fertility and crop reaction dependant S fertilizers or any secondary amendments would be optimized for those of climate specific. Attempts should be customized on evaluation of various industrial by-products as a potential foundation of S fertilizers. In addition to develop such a model for sufficient release of sulfate residues from organic derivatives based on significant proportion of organic S fertilizers (around 80% of total S in soil worldwide) would be important. An understanding of underlying mechanism of soil leaching and other weathering of S containing minerals loss of the elements may cultivate the regulation measure of plants nutrients. Finally, suitable plant ideotypes for harnessing improved sulfur utilization efficiency and its related assimilatory potential in support to crop development and sustainability, stress tolerance, nutrient delivery and assimilation, satisfactory yield potential must be incorporated in breeding programme for better S management and crop practice.

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Reducing Methane Emission from Lowland Rice Ecosystem

25

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Abstract

Reduction in the emission of methane is a challenge to the global scientific community. The global warming potential of methane is about 28–36 making it capable of trapping heat in the atmosphere and contribute to global warming. In this chapter we have described the mechanism and various pathways of methane formation, and discussed the mechanism of methane transport to atmosphere by diffusion, aerenchyma transport, and ebullition. Apart from this, we have also narrated various microbial and non-microbial sources of methane and various factors that control methane emission. Aerobic methane oxidation is a process by which methane produced under anaerobic environment are oxidized to carbon dioxide by methanotrophs, which has been explained in this chapter. Besides, we have discussed various methodologies of water, fertilizer, manure management for controlling methane emission.

25.1 Introduction

Methane is a greenhouse gas (GHG) and significant contributor to climate change (Chatterjee et al. 2020). A large quantity of methane (CH_4) is coming from natural (marshy or boggy area) and anthropogenic (rice paddy) wetlands accounting around 20–50% of its emissions on a global scale (Ciais et al. 2013). The global warming potential of CH_4 is about 28–36 times over 100 years which makes it more capable

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of trapping heat in the atmosphere (IPCC 2014; Chatterjee et al. 2018; Swain et al. 2018a, b, c). Moreover, the global atmospheric CH_4 emission increased from 700 ppb to 1808 ppb over past 260 years (IPCC 2014). In India, agriculture contributes about 16% of India's all out GHG emission, emitting 417.22 million tons of carbon dioxide (CO_2) equivalent every year, of which 74% is CH_4 and 26% is nitrous oxide (N_2O) (MoEFCC 2018). Contribution of agricultural soil is about 20% to the total CO_2 emission through plant root and soil microbial respiration, 12% of total CH_4emission, and 60% of the total N_2O emissions (IPCC 2007).

Anaerobic soil environment is the primary source of CH_4 emission from microbial degradation of organic substances in soil under low redox potential. Under anaerobic condition, the soil microbes hydrolyze the complex organic compounds (e.g. proteins, polysaccharides, and fats) to H_2, CO_2, and acetate. In the second step, H_2, CO_2, and acetate are reduced to CH_4 by methanogens (Thauer et al. 2008). The CH_4 produced in the soil then enters into the rice roots and is transported through the arenchyma system, finally released to the air. During this process, a part of CH_4 is also oxidized at top oxygenated soil layer. About 90% of total methane produced in wetland rice soils got oxidized before getting release to atmosphere (Rothfuss and Conrad 1998). The balance between net CH_4 source and sink in soil environment primarily depends on the relative rates of methanogenic and methanotrophic activity. Soil organic matter in flooded soil or lake sediments are the primary source of dynamic activity of methanogens and methanotrophs emitting CH_4 to atmosphere (Bhaduri et al. 2017).

Globally agriculture accounted 47% of total anthropogenic CH_4 emissions (USEPA 2006; IPCC 2007). Enteric fermentation of livestock has the highest share (64%), followed by the significant contribution from wetland rice agriculture (22%). Therefore, flooded rice soils are the major source of the global biogenic CH_4 emission with an average life time of 10 years in agriculture (37 Tg $year^{-1}$; IPCC 2007). In lowland rice agro-ecosystems, the generated CH_4 in flooded anaerobic soil environment are emitted through diffusion, ebullition, and aerenchyma cells in rice plants (Saha et al. 2018) that accounts 1.5% of total GHG emissions (Adhya et al. 2014). Under ample organic substrate availability, ebullition dominated over CH_4 diffusion through the overlying flood water particularly during early crop growth stages of lowland rice. The methane source strength of rainfed upland rice is uncertain because of high spatiotemporal variability in sink strength against wetland rice agriculture in lowland agro-ecosystems.

Methane emission from agricultural production system depends on the management practices especially soil, water, and crop managements. Reducing emission of CH_4 is one of the major challenges in agriculture. Appropriate management of water resources, right sources of fertilizer and application of appropriate organic manure reduce methane emission. Apart from management practices, methane emission from rice field is largely controlled by texture, soil organic carbon content, temperature, and pH of the soil (Li and Wang 2004). Various internal factors like selection of rice cultivar and soil microbial dynamics in soil also control CH_4 emission. The net CH_4 emission from rice field is the balance between its genesis and oxidation in soil.

25.2 Mechanism of Methane Formation and Transport

25.2.1 Mechanism of Methane Formation

Methane is formed under low Eh conditions (<-200 mV) by methanogenic microbes through decomposition of organic matter and rice root exudates (Forster et al. 2007; Philippot et al. 2009). Methane emission is also related to the above-ground biomass that enhances photosynthate synthesis, a part of which is then mobilized to the roots, and it is used as a substrate for methanogens (Gutierrez et al. 2013). Methanogens are prokaryotic microorganisms belonging to archaea and they prefer an anaerobic environment. There are two main pathways of CH_4 formation, acetoclastic in which the methanogens use acetate (contributes 80% to CH_4 synthesis) and hydrogenotrophic in which H_2/CO_2 (contributes 10–30% to CH_4 formation) is used as substrate (Yuan et al. 2019). Acetate and H_2 are formed due to the fermentation of organic matter (Segers 1998) and flooding of rice fields hinders oxygen to enter into the soil resulting in anaerobic environment that promote formation of CH_4 (Ferry 1992). Then a part of formed CH_4 escapes from the soil into the air through rice roots and stems, and the rest of CH_4 releases from the soil through diffusion (Lu et al. 2000). However, a part of CH_4 is also oxidized by methanotrophs in the rhizosphere to CO_2.

25.2.2 Methane Transportation from Paddy Soil to Atmosphere

Methane transportation process from soil to atmosphere consists of three pathways: (1) transport through rice plants via aerenchyma, (2) ebullition in the form of bubble; and (3) diffusion through the standing water (Tokida et al. 2013; Green and Baird 2012) (Fig. 25.1). The relative contribution of these three processes are about 90% for aerenchyma transport, 9–10% for ebullition and 1% for diffusion.

1. Aerenchyma transport (plant-mediated transport)—In this process, the CH_4 formed in soil is emitted into the atmosphere via aerenchyma. Aerenchyma is viewed as one of the vital components in methane emission that is found in roots, internodes, and leaf (Steffens et al. 2011). Methane transported through aerenchyma avoids oxidation in the oxygenated soil layer by methanotrophic bacteria. However, the aerenchyma not only transports CH_4, but also oxygen that helps in oxidizing a part of methane by methanotrophs in the rhizosphere itself (Win et al. 2011). Abiotic factors including pH, Eh, temperature, availability of nutrients, and depth of water influenced the CH_4 reaching the atmosphere by this process (Stanley and Ward 2010). Besides, the transportation of CH_4 to the atmosphere depends upon the rice variety, permeability coefficients of aerenchyma, and concentration gradients of CH_4 in between the roots and inside of aerenchyma. The CH_4 emission by this process accounting for about 60–90% of the total CH_4 produced in rice fields indicating the potential of selecting suitable rice varieties in controlling CH_4 emissions (Liou et al. 2003).

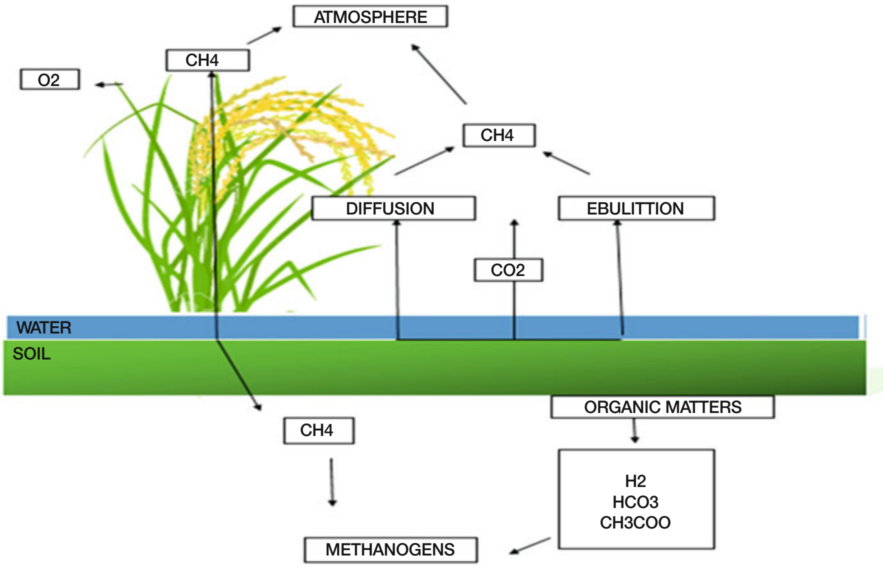

Fig. 25.1 Mechanism of methane transport

2. Ebullition—It is the quick discharge of CH_4 bubbles from the soil to the atmosphere, which is occurring due to temperature fluctuations, buildup of pressure gradient, and sudden drop in soil moisture. This type of CH_4 transport is also influenced by spraying, rainfall, groundwater movement, evaporation, and wind. This method of transport is more dominant in peat land and it is classified as steady ebullition and intermittent ebullition (Coulthard et al. 2009). Steady ebullition refers to the constant steam flow of CH_4 bubbles, while in the intermittent ebullition the CH_4 releases periodically.
3. Diffusion—This method of CH_4 transport occurs due to the difference in concentrations of CH_4 in between the soil air and atmospheric air. The diffusion of CH_4 largely depends upon the soil properties especially on porosity and permeability of the soil and the amount of CH_4 left after oxidation by methanotrophs in the oxygenated soil layer.

25.3 Sources of Methane Emission in Nature

Methane is formed mainly under anaerobic environment by methanogens, viz. wetlands, lakes, oceans, rice fields, livestock, sewage, and landfills. Besides, there are various non-microbial sources of CH_4 emission like biomass burning (Andreae and Merlet 2001) and the Earth's crust (Etiope and Klusman 2002). Non-microbial CH_4 may also be generated by plant leaves when they were incubated under anaerobic conditions (Wang et al. 2009).

Wetlands are a critical CH_4 emission source, representing 82% of the methane emission on Earth (USEPA 2010) due to the comparatively low dissolved oxygen and high in flow organic concentrations (Mander et al. 2008). Freshwater lakes cover 2–3% of land surface on Earth (Downing et al. 2006) and contribute 8–48 Tg CH_4 per annum (Bastviken et al. 2004). However, oceans have very large coverage but they account for approximately 3% of global CH_4 emissions (Neef et al. 2010). This may be attributed to its high sulfate (SO_4^{2-}) content (28 mM) that reduce the dependencies on methanogenic organic matter degradation and also because of oxidation of CH_4 in water column (Knittel and Boetius 2009). Rice as a sole crop emits 25 MT CH_4 (12% of agricultural contribution) globally and 3.5 MT CH_4 (18% of agricultural contribution) in India (Pathak et al. 2018). Mainly, irrigated rice is raised within bunded fields, which keeps about 5–8 cm water standing inside fields. Methane is produced in waterlogged paddy fields by anaerobic decomposition of soil organic matter (Minamikawa et al. 2010). Livestock sector contributes about 18% to the global anthropogenic greenhouse gas emissions accounting for 37% and 65% of CH_4 and N_2O, respectively (FAO 2006). Sewage and landfills contributed to CH_4 emission and it was observed that the gas generated from sewage and landfill contained approximately 45–60% CH_4. It is estimated that global methane emission from landfills is about 10% (~36 Tg) of all anthropogenic sources (USEPA 2006).

25.4 Factors Controlling Methane Emission in Agro-Ecosystem

Methane budget is lowland rice primarily depends on three crucial factors, viz. substrate availability for methanogenesis, efficiency of plant-mediated transport through aerenchyma cells, and availability of active CH_4-oxidizing site in rhizosphere (Win et al. 2011; Zheng et al. 2014). However, the effective environmental controls on CH_4 emission from wetland rice agriculture are may be categorized:

1. *Soil reaction (pH)*: The favorable soil pH for optimum methanogen activity varies between 6.5 and 7.5 (neutrophilic). Methanotrophs favored acidic Soil pH (4.3–5.9; Kamal and Varma 2008). Methanogen are sensitive to soil acidity. The optimum pH ranges for CH_4 production and consumption varies between 5.5 and 7.0 and 5.0 and 6.5 soil pH range, respectively (Dunfield et al. 1993).
2. *Soil redox potential (Eh)*: Lower redox potential (<-100 mV) in Anaerobic condition facilities methanogenesis (Hou et al. 1998). The critical soil Eh varies from -150 to -160 mV for initiation of CH_4 production. For every 50 mV decrease in soil redox level, tenfold increase in soil CH_4 emission is inevitable within the soil Eh range from -150 mV to -250 mV (Masscheleyn et al. 1993). Between -230 and -150 mV soil Eh range, the exponential negative correlation exists between CH_4 production and soil Eh of surface soil layer (Wang et al. 1993).
3. *Soil organic matter*: The readily oxidizable bio-degradable organic substrates are the precursor of anaerobic degradation via methanogenesis in wetland rice soils through lowering of soil Eh (Denier Van der Gon and Neue 1994; Win

et al. 2011; Saha et al. 2018). Earthworm activity in top soil layers increases soil aeration; thereby decreases CH_4 emissions from anoxic soil environment (Mitra and Kaneko 2017).

4. *Soil salinity*: Soil salinity (EC > 4.0 dS m^{-1} in low sulfate containing soil) ensures the availability of terminal electron acceptors in flooded wetland rice soil and reduces CH4 emission by 3–4 times from soil environment (Denier Van der Gon and Neue 1995; Sahrawat 2004). Enhanced SO_4^{2-} concentration from gypsum application reduced CH4 emission (55–70%), particularly due to inhibition of methanogenesis by sulfate-reducing bacteria (Denier Van der Gon and Neue 1994).
5. *Soil texture*: Coarse-textured sandy loam soils facilitate oxygen entry in soil environment that promotes CH_4 oxidation. Under similar production system, identical rice cultivar and uniform N fertilization schedule CH_4-C from clay soils were 23% less than silt-loam under warm humid environment (Brye et al. 2013). The silt content (optimum range 30–71%) in the soil played the crucial role for determining the CH_4 production potential of soil (Setyanto et al. 2002). Nevertheless, enhanced CH_4 entrapment in heavy soils amplifies CH_4 oxidation and retards CH_4 emission to atmosphere (Neue 1993). Higher pore size in coarse-textured soils (sand to silt loams) facilitates CH_4 movement; whereas, pore tortuosity slow down the dominated mode of CH_4 transport through diffusion in fine-textured soils (Hillel 2004).
6. *Soil structure and porosity*: Moist, well-aerated soils (moderate soil matric potential) with high soil porosity favored CH_4 oxidation, while waterlogged anaerobic condition (higher soil matric potential) facilitates CH_4 synthesis in soil environment (Ball et al. 1997). Increase in air permeability and relative diffusivity promotes CH_4 oxidation in soil environment (Ball et al. 1997). Oxidation of atmospheric CH_4 in well-drained soils accounts for 10% of the global CH_4 sink (Topp and Pattey 1997). Increased bulk density in compacted soil layer retards CH_4 production in wetland rice soil (Carter et al. 2011).
7. *Soil moisture content*: Optimum soil moisture level is crucial to maintain the activity of soil biota (methanotrophs and methanogens). Limited oxygen supply in saturated soil environment (reduced condition) facilitates methanogenesis and increased methanotrophs activity under oxygenated environment facilitates CH_4 oxidation in moist arable soils. The CH_4 oxidation is often restricted from the diffusion limitation at higher soil moisture regime and desiccation stress on soil biota under moisture deficit stress (Zhang et al. 2016). Control environment studies prescribed between 20 and 50% water filled porosity for optimum CH_4 oxidation (Dunfield 2007). The downward flux of percolating water moving towards the groundwater table curtail substrate availability to methanogens, thereby further reduces net seasonal CH_4 production and subsequent emission from the soil environment (Inubushi et al. 1992; Yagi et al. 1998). Diffusion and convective flow dominated the CH_4 transport mechanism in unsaturated soil environment (Hillel 2004).
8. *Soil temperature*: Seasonal and daily soil temperature is positively correlated with rise in daily and cumulative CH_4 formation and emission between 4 and

37 °C (Yang and Chang 1998). The rate of CH_4 emission doubled for each degree rise in soil temperature from 20 to 25 °C (Holzapfel-Pschorn and Seiler 1986; Sass et al., 1991). Beyond 34.5 °C, reduced methanogenesis accounted the sharp decline in CH_4 emission from flooded rice soils (Parashar et al. 1993).

9. *Rice cultivar specificity*: Variation in crop vigor, phenology, rooting behavior, and metabolic activities in different rice varieties sourced the cultivar specific variation in seasonal CH_4 emission (Kerdchoechue 2005). The hybrid semi-dwarf rice varieties emitted less CH_4 than tall traditional rice varieties (Lindau et al. 1995; Neue et al. 1996). In general, the CH_4 emission from Indica rice was higher than japonica type (Inubushi et al. 2011; Yun et al. 2012). Higher plant density stimulated CH_4 production, but did not result in higher CH_4 emission rates in semi-dwarf, tall, and hybrid cultivars in rice (Wassmann et al. 2002). In wetland rice cultivation under prolonged submergence, maximum CH_4 emission occurred during maximum tillering to panicle initiation stage from the higher rice root activity, reduced CH_4 oxidation rate, and better plant-mediated aerenchyma transport of CH_4 mechanism (Bhatia et al. 2011; Suryavanshi et al. 2012). Root biomass and growth duration has the most effective control on the yield scaled CH_4 emission in lowland rice (Zheng et al. 2014).
10. *Crop management practices*: Field management practices have substantial potential in reducing CH_4 emission from wetland rice fields. The brief account on potential field management practices for reducing CH_4 emission in lowland rice agro-ecosystems are as follows.
    a. *Organic residue application*: Organic amendments application (crop residue, green manure, compost, farmyard manure, etc.) in flooded rice paddy soils increased the CH_4 emission during active crop growth period (Johnson-Beebout et al. 2009; Thangarajan et al. 2013). Well decomposed or humified organic matter emits 20% less than fresh application (Khosa et al. 2010; Pramanik and Kim 2014).
    b. *Tillage practices*: Tillage and crop residue retention influenced CH_4 emission through the modification of soil porosity, soil temperature, and soil moisture. Conversion of conventional tillage to no-till significantly reduced CH_4 emission from soil environment likely, no-till < rotary tillage < conventional tillage (Li et al. 2011; Zhang et al. 2013). In contrast, some studies confirmed no significant effect in CH_4 emissions under conservation tillage practice (Ussiri and Lal 2009; Dendooven et al. 2012). Increased compaction facilitated CH_4 oxidation in surface soil layer under no-till condition (Smith et al. 2001). However, cropping system and seasonality also regulated the soil CH_4 emission under no-till practices (Bayer et al. 2012).
    c. *Fertilizer nitrogen application*: Mineral N fertilizers inhibit CH_4 oxidation due to ample availability of NH_4^+ and C substrate from enhanced plant C assimilation for methanogenesis (increased dissolved organic carbon), thereby CH_4 emissions increased dramatically (Dubey 2003; Bayer et al. 2012). The net impact of N fertilizer application on enhanced CH_4 emission sustained during subsequent flooded fallow period (Xu et al. 2020).

d. *Flooding pattern in wetland rice culture*: Alternate drying and wetting cycles controlled irrigation reduced CH_4 emission and saved water in rice agriculture without any significant yield loss and seasonal total N_2O emission from lowland rice paddy (Adhya et al. 2014; Setyanto et al. 2018).

11. *Climate change*: Our present day global climate variability has profound impact on CH_4 emission from wetland rice agro-ecosystems both under tropical and temperate climate system (Ray et al. 2020). The combined rise in either atmospheric CO_2 concentration and air temperature (beyond 30–35 °C threshold; Minami and Neue 1994) enhanced substrate availability for methanogenesis through rapid soil organic matter decomposition, greater root exudation, and rhizodeposition (Das and Adhya 2012; Gaihre et al. 2013). Several atmospheric CO_2 enrichment and elevated temperature studies also confirmed the obvious potential to enhance CH_4 emission from rice agro-ecosystem under variable scenarios of projected environmental change (Chatterjee and Saha 2018; Chatterjee et al. 2019a; Saha et al. 2020).

25.5 Aerobic Methane Oxidation

Methane oxidation is a microbial process in which CH_4 is used in metabolic process for generation of energy and assimilation of carbon by a group of bacteria known as methanotrophs. This is basically a special type of respiration involving methanotrophs. In this process, the methane is oxidized in the presence of oxygen to less harmful gas, CO_2. Occurrence of this process is highly beneficial on environmental point of view.

In the process of methanotrophy, CH_4 is oxidized with molecular oxygen to a series of intermediate products like formate, methanol, formaldehyde and finally to CO_2 (Madigan et al. 2003; Bowman 2006). This microbial process involves a special type of enzyme, methane monooxygenase which involves in the oxidation of CH_4 with molecular oxygen to form methanol and water as products. Broadly, these enzymes are of two types—particulate methane monooxygenase containing Cu and soluble methane monooxygenase containing Fe (Hanson and Hanson 1996). Particulate methane monooxygenase is more dominant among the methanotrophs.

Diffusion of oxygen through aerenchyma in rice is primarily involves in aerobic CH_4 oxidation by methanotrophs. In rice ecosystem, it is estimated that about 40–90% of the produced CH_4 are converted to CO_2 by methanotrophs before it is emitted (Megonigal and Schlesinger 2002). Hence, the presence of higher and diversified population of methanotrophs in wetland ecosystems especially in rice paddy makes the system more environmentally feasible. Methanotrophs varied widely in rice fields depending upon the situations (Ho et al. 2016), as their population is increased within 0–2 cm of rice soils and higher population id detected during the rice growing periods (Macalady et al. 2002). Amid-season drainage or alternate wetting and drying encourages the methanotrophs population that further stimulates the CH_4 oxidation activity in rice soils (Ma and Lu 2010).

25.6 Techniques for Reducing Methane Emission

25.6.1 Chemical Methods

25.6.1.1 Application of Suitable Chemical Fertilizer

Right source of fertilizers, especially N containing fertilizers, is an important factor in controlling emission of most of the greenhouse gases to atmosphere (Pathak et al. 2016, 2019). Application of sulfur containing fertilizer (for example, ammonia sulfate) and sulfate amendments (for example, gypsum) decreases CH_4 emission from rice fields (Adhya et al. 1998). It was observed that application of ammonium sulfate to rice field decreased CH_4 emission by 25–36% (Metra-Corton et al. 2000). Application of phosphogypsum along with urea reduced CH_4 emission by more than 70%.

Importance of potassium management in lowland rice for higher productivity is already established (Das et al. 2018). Potassium source like muriate of potash (KCl) reduces emission of CH_4 in rice paddy. Application of 30 kg K ha^{-1} is reported to reduce CH_4 emission by 49% (Babu et al. 2006). Potassium application to rice soils reduces active reducing substances in the rhizosphere soil. Subsequently, it hinders methanogenic organisms and stimulate methanotrophic bacterial population (Babu et al. 2006). In potassium inadequate soils uses of potassium fertilizer increase yields and additionally decrease the CH_4 emission, may be proved as a useful technology for lowland rice.

25.6.1.2 Application and Synthesis of Right Organic Manure

Organic manures account for almost 10% of GHG emissions from agriculture globally (Owen and Silver 2015) and 1% of the total emission in India (Pathak 2015). Vermicompost contained higher N content compared to conventional farmyard manure and compost (Chatterjee et al. 2016b) and requirement of vermicompost is almost half of the dose of farmyard manure. Application of lower quantity of carbon through vermicompost than farmyard manure could reduce the supply of C to methanogens. During production of anaerobic composts, vermicomposts CH_4 is produced as a by-product. It was observed vermicomposting reduces 22–26% CH_4 emission compared thermophilic composting during their production (Nigussie et al. 2016). Application of fermented manure such as biogas slurry in place of unfermented farmyard manure reported to reduce CH_4 emission (Pathak et al. 2010).

25.6.1.3 Nitrification Inhibitors

Some nitrification inhibitors like dicyandiamide and calcium carbide can moderate CH_4 emissions from rice fields (Bronson and Mosier 1994; Bhatia et al. 2010). In flooded rice, use of wax covered calcium carbide can reduce CH_4 emissions extensively. The decrease in CH_4 emissions can be attributed to the release of acetylene which inhibits methanogenesis (Lindau et al. 1993).

25.6.1.4 Application of Biochar

Biochar, a recalcitrant carbon material, is used as a soil amendment (Lehmann 2006; Munda et al. 2018). It enhances plant development and improves soil properties (Lehmann and Rondon 2005, 2006; Glaser et al. 2002). Due to less labile carbon content is more in biochar, it may be highly useful in reducing CH_4 emission.

25.6.2 Agronomic Management

25.6.2.1 Water Management

Rice field is different from other arable crops as 5–8 cm water is standing on soil, which resulted in altogether different energy balance, carbon balance, and water balance exist in rice ecosystem (Chatterjee et al. 2019b, c, 2021; Swain et al. 2018a, b, c; Gautam et al. 2019). Such special situation in rice field due to standing water causes significant amount of CH_4 emission. Mid-season drainage of surface flood water from the rice field for seven days at the end of tillering reduces CH_4 emission from rice field. This method of water management circulates air through the soil and subsequently hindering CH_4 production from 7 to even up to 95% with little impact on rice grain yield and it additionally supports root improvement by stimulating rapid decomposition of organic matter that supply more mineralized nitrogen for plant uptake. However, one drawback of mid-season drainage is increased in N_2O emission propelled due to unsaturated soils conditions (Zou et al. 2005). Practice of multiple aeration of field by alternate wetting and drying (AWD) is also useful in reducing CH_4 emission (Nayak et al. 2020).

25.6.2.2 Dry Direct Seeded Rice Cultivation

Dry direct seeded rice cultivation involves planting of seeds under dry field directly. This technique reduces the time a field under standing water, restricts the action of methanogens, thereby reducing CH_4 emissions. In addition to this, rice producers can realize significant cost savings by reduction in the labor required to transplant rice and manage flooding. Direct seeding on wet and on dry soils reduced CH_4 emission by 8% and 33%, respectively, as compared to transplanting (Ko and Kang 2000).

25.6.2.3 Crop Residue Management

Crop residue management is an important aspect in conservation agriculture (Chatterjee 2016). However, application of organic residue such as rice straw to soil stimulates CH_4 emission (Denier Van der Gon and Neue 1995). Rice straw contains high labile C that upon soil incorporation and flooding results in a drop in soil redox potential which is congenial for CH_4 formation. However, in comparison to straw burning, incorporation of rice straw before wheat in India or vegetable in the Philippines and China showed reduction of CH_4 emissions to the tune of 0.4 t carbon equivalent ha^{-1}(Wassmann and Pathak 2007). Application of fertilizers to the soil before straw application decrease CH_4 emissions under continuous flooding condition by 58% compared to only straw application under continuous flooding (Wassmann et al. 2000).

25.6.2.4 Crop Diversification

Instead of monocropping with rice in rice-rice ecosystem, crop diversification through rice-maize, rice-greengram/blackgram, rice-groundnut can reduce CH_4 emission significantly (Lal et al. 2019). For example, diversification of rice-rice system to rice-maize in upland situations in Philippines reduced CH_4 emission by 95–99% (Nayak et al. 2020). Although annual N_2O emissions increased two- to threefold in the diversified systems, the strong reduction in CH_4 led to a significant reduction in annual global warming potential as compared to the traditional double-rice cropping system (Nayak et al. 2020). Interestingly, conversion of rice-rice to rice-fallow reduces the total CH_4 emission on system basis, however, the later system lacks poor economic return. Hence, crop diversification practices to utilize rice fallows for higher system productivity are advised (Gautam et al. 2021).

25.7 Future Research Perspective

Methane emission can be controlled by above chemical and agronomic methods, however, development of suitable cultivar of rice that can reduce aerenchyma transport, mineralogical control of soil carbon (Chatterjee et al. 2013, 2014a, b, 2015a, b, 2016a) in controlling CH_4 emission, long-term application of fertilizer and manure on community structure of methanogens and methanotrophs (Kumar et al. 2018), use of inhibitor of methanogenesis need to be explored in future. Methanogens are responsible for production of CH_4 which can be prevented by introduction of certain chemical inhibitor. Methanogens inhibitor may inhibit CH_4 emission up to 60% in livestock (Hristov et al. 2013), but application of these inhibitors in agricultural field is limited (for example, propynoic acid) (Ungerfeld et al. 2004; Zhou et al. 2011).

25.8 Conclusion

Approximately, 70–80% of the total annual global CH_4 emission is contributed by livestock and agriculture sector including rice paddies, biomass burning, waste disposal, and natural wetlands and will continue to rise in near future. Controlling CH_4 emission requires attention to curbing the supply of active sources of C enriched substrate, preventing anaerobic environment (Eh <-200 mV) to prevail for long time and controlling the population of methanogens by suitable agronomic management practices. However, while choosing the right practices, one should consider that the productivity of the crop should not decline much than that of the prevailing practices to make the technology more acceptable to the farmers.

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Potential and Risk of Nanotechnology Application in Agriculture *vis-à-vis* Nanomicronutrient Fertilizers

26

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Abstract

Nanotechnology had a wide potential of its novel applications in the fields of plant nutrition to meet the future demands of the growing population because nanoparticles (NPs) have unique physicochemical properties, i.e., high surface area, high reactivity, tunable pore size, and particle morphology. Management of optimum nutrients for sustainable crop production is a priority area of research in agriculture. In this regard, nanonutrition concerns with the provision of nanosized nutrients for sustainable crop production. The application of nanomaterials for delivery of nutrients and growth-promoting compounds to plants has become more and more popular and their utilization at the proper place, at the proper time, in the proper amount and of the proper composition affects the use efficacy of fertilizers. Using this technology, we can increase the efficiency of micronutrients delivery to plants. In the literature, various NPs and nanomaterials (NMs) have been successfully used for better nutrition of crop plants compared to the conventional fertilizers. This review summarizes the synthesis of nanofertilizers, characterization of nanofertilizers, NPs, and NMs as micronutrient fertilizers and describing their role in improving growth and yield of crops, uptake, translocation, and fate of nanofertilizers in plants and environmental hazard of NPs and NMs application.

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Keywords

Health hazard · Nanomicronutrient fertilizers · Nanonutrition · Nanotechnology · Risk assessment

26.1 Introduction

Nanotechnology is one of the unique technologies of the twenty-first century. In the last decade, a large variety of nanomaterials (NMs) have been developed and used under the umbrella of nanotechnology in multifaceted sectors (Lien et al. 2017). The basis of nanotechnology was laid by Nobel laureate Richard P. Feynman through his popular lecture "There's Plenty of Room at the Bottom" (Feynman 1960). Taniguchi (1974) first coined the term nanotechnology and stated that nanotechnology consists of the processing, separation, consolidation, and deformation of materials by one atom or one molecule. The term "nanotechnology" is based on the prefix "nano" which hails from the Greek word meaning "dwarf." It is usually employed for materials having a size ranging from 1 to 100 nm (NNI 2009). Several researches had been awarded Nobel Prize for the development of nanotechnology (Table 26.1).

Nanotechnology, according to Joseph and Morrison (2006), is the modification or self-assembly of individual atoms, molecules, or molecular clusters into structures in order to produce materials devices with new or drastically different properties. Nanotechnology is the design, fabrication, and utilization of materials, structures, devices, and systems through control of matter on the nanometer length scale and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale in at least one dimension. Table 26.2 enlisted the size distribution of various natural and fabricated nanoparticles (NPs). At nanoscale, the chemical and physical properties of material change and surface area of material are large compared to its volume. This makes material more chemically reactive and changes the strength and electrical properties of material compared to the bulk counterpart. The synthesis protocols for diverse nanoparticles (NPs) were established and advanced to the molecular level (Gugliotti et al. 2004).Generally, it works by following the top-down (includes reducing the size of the smallest structures to the nanoscale) or

Table 26.1 Prizes for elucidating atoms and subatomic particles

Winners	Achievement	Nobel prize in the year
Gerd Binnig and Heinrich Rohrer	Scanning tunneling microscope	1986
Hans Dehmelt and Wolfgang Paul	Traps to isolate atoms and subatomic species	1989
George Charpak	Subatomic particle detectors	1992
Clifford Schull and Bertram Brockhouse	Neutron diffraction technique for structure determination	1994
Steven Chu, Claude Cohen Tannoudji, and William Phillips	Methods to cool and trap atoms with laser light	1997

Table 26.2 Comparison in size between natural and fabricated nanoscale objects

Object	Diameter (nm)
Hydrogen atom	0.1
Buckminsterfullerene (C_{60})	1.0
Six carbon atoms aligned	1.0
DNA (width)	2.0
Nanotube	3–30
Proteins	5–50
Quantum dots (of CdSe)	8.0
Dip pen nanolithography features	10–15
Microtubules	25
Ribosome	25
Virus	75–100
Nanoparticles range from	1–100
Semiconductor chip features	90

the bottom-up (comprises manipulating individual atoms and molecules into nanostructures with nearly similar chemistry or biology) approach.

Nanotechnology has emerged as a cutting-edge technology, acting as a convergent science that attracts a plethora of disciplines (environmental science, energy, plant science, agriculture, materials physics, and nanomedicine) and sectors closely linked with human welfare (Gruère 2012; Dasgupta et al. 2016). The application of nanotechnology in various fields anticipated to be advantageous for society and the environment, reduce the cost of input and cause inflation, boost the quality of goods, open opportunities for jobs (Hansen et al. 2008). A wide range of applications of nanotechnology have emerged into the "agrifood sector" which include the nanosensors, tracking devices, targeted delivery of required components, food safety, new product developments, precision processing, smart packaging, nanofertilizers, and others (McClements et al. 2009; Huang et al. 2010; Ranjan et al. 2014; Dasgupta et al. 2016). Nanotechnology can also improve the water solubility, thermal stability, and bioavailability of the functional compounds of food (McClements et al. 2009; McClements and Li 2010). The use of NPs imparted tremendous efficiency compared to bulk particles or particulate matter (PM) because of their large specific surface area, diverse functionalities, easy functionalization, the presence of active sites on the surface, extraordinary electrical and optical properties, extremely high stability, and high adsorption capacity (Boparai et al. 2011; Zhao et al. 2014; Choi et al. 2015; Jiang et al. 2015; Kumar et al. 2015).

26.2 Applications of Nanotechnology in Agriculture

The present day agriculture is facing many challenges, such as changing climate due to the greenhouse effect and global warming; urbanization due to life pattern changes; non-judicious use of resources like petroleum, natural gas, high-quality rock phosphate, etc., that are non-renewable; and environmental issues like run off,

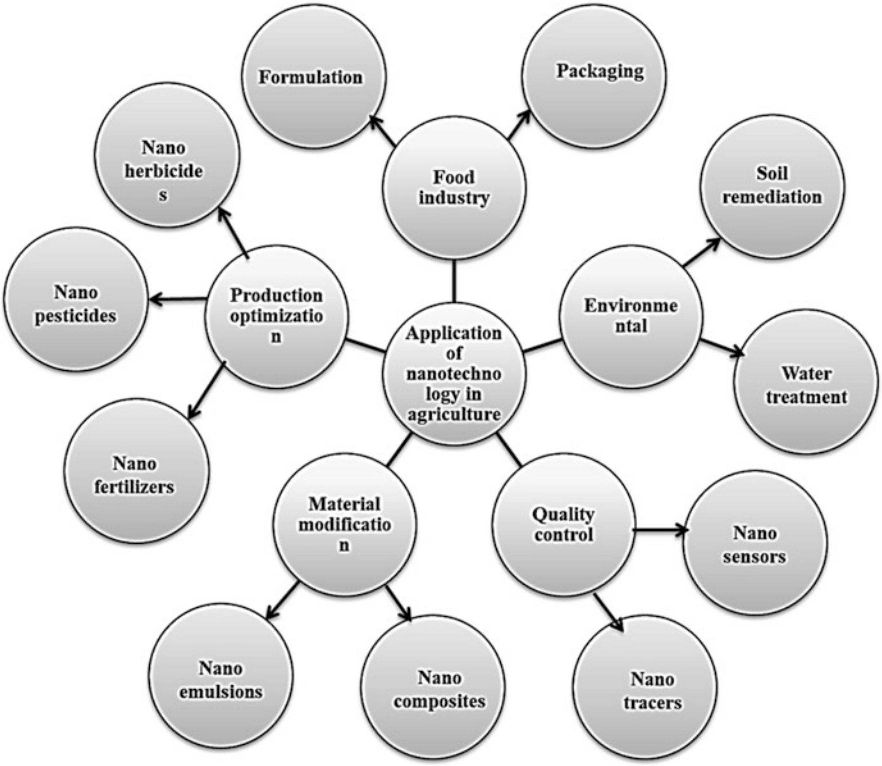

Fig. 26.1 Nanotechnological developments in agricultural field

eutrophication related with the application of more chemical fertilizers than required. These problems get more intensified by the world population, which is increasing at an alarming rate and is expected to reach 9.6 billion by the year 2050 (Desa 2008). The demand for global food production has increased during the last two decades. An increase by 70% in global grain production is required to feed this increasing world population (FAO 2009). Agriculture has always been the backbone of most of the developing countries to fuel the growth of economy. According to 2014–2015 estimates, India's population is 1.27. With the concern of providing food to such a big population, there is a need of new technology in agriculture giving more yields in short period.

A significant increase in agricultural production could be achieved through utilization of nanotechnology for efficient nutrient management system, good plant protection practices, efficient photocapturing system in plants, precision agriculture, and many others (Tarafdar et al. 2013; Prasad et al. 2014) (Fig. 26.1). Table 26.3 showed the cosmparison between nanofertilizers and conventional products. Applications of nanotechnology in materials science and biomass conversion technologies applied in agriculture are the basis of providing food, feed, fiber, fire,

Table 26.3 Property comparison between nanofertilizers and challenges in their applicability

Property	Nanofertilizer	Challenges	References
Controlled release	Nanofertilizers can control the speed and doses of nutrient solution release	Reactivity and composition variations due to environment factors	Duhan et al. (2017)
Nutrient loss	Leakage and waste caused by application of fertilizers can be reduced	Environmental effects after conclusion of the nanofertilizer life cycle	Chinnamuthu and Boopathi (2009)
Duration of release	Nanofertilizers can extend the duration of nutrient release in comparison with regular fertilizers	Phytotoxicity effects due to the dose and time of exposure	Servin and White (2016)
Efficiency	The uptake ratio is increased and the release time of nanostructures is reduced	Long-term environmental effects, as well as chronic effects on final consumers	Ditta and Arshad (2016)
Solubility and dispersion	Absorption and fixation of nutrients by the soil are improved, increasing their bioavailability	Complete ecotoxicological profiles, taking into account the consequences for health and the environment	Prasad et al. (2017)

and fuels. Nanotechnology provides a number of cutting-edge techniques for improving precision agricultural practices and allowing precise monitoring at the nanoscale level. In agriculture two types of nanomaterials are mostly used: (1) carbon based single- and multi-walled carbon nanotubes, (2) metal based aluminum, gold, zinc, and metal oxide based ZnO, TiO_2, and Al_2O_3. Single and multi-walled carbon nanotubes are used as nanosensors and plant regulator to enhance plant growth (Khodakovskaya et al. 2012). Nanosilica is used in filtration of food and beverages and packaging. Metal oxides like ZnO, TiO_2, and Al_2O_3 are used in nanofertilizers to boost the crop growth (Gogos et al. 2012; Sabir et al. 2014).

Application of nanotechnology has been regarded as an innovative and promising technology for sustainable agriculture, to feed the ever-increasing population of the world. It has revolutionized agriculture with innovative nutrients in the form of nanofertilizers (NFs), nanopesticides, and efficient water management system (Ditta and Arshad 2016). Conventional fertilizers with low use efficiency (20–50%) and cost-intensive increase in application rates have increased to develop and promote the use of NFs (Aziz et al. 2006). Many scientists worldwide have focused on this innovative field and have developed such NPs and NMs that could serve as nutrients for the plants (Liu and Lal 2015).

For agricultural use, it is preferable to have particle having size less than 20 nm, polydispersity index less than 1, zeta potential value apart from +30 mV and −30 mV, and mostly cubed shaped particle to enter through the plant pores (Tarafdar et al. 2012). Nanoparticles can be synthesized by physical, chemical, physicochemical (aerosol), and biological techniques. Grinding, thermal evaporation, sputtering, and pulse laser deposition technique are important physical methods. Chemical synthesis includes the technique like sol gel, co-precipitation, microwave synthesis, micro-encapsulation, hydrothermal methods, polyvinylpyrrolidone (PVP) method, and sonochemistry.

26.3 Nanofertilizers

Nanofertilizers are modified fertilizers synthesized by chemical, physical, or biological methods using nanotechnology to improve their attributes and composition, which can enhance the productivity of crops (Singh et al. 2017; Mahto et al. 2021). Nanofertilizers are nanomaterials that can supply one or more nutrients to the plants and enhance plant growth and yields or those that can improve the performance of conventional fertilizers but do not directly provide crops with nutrients. There are several advantage of using nanoformulation of fertilizers in agriculture (Table 26.4). Nanofertilizers can be classified as macronutrient nanofertilizers and micronutrient nanofertilizers (Fig. 26.2). Compared with the conventional fertilizers, these nanofertilizers are expected to significantly improve crop growth and yields, enhance the efficiency of fertilizer use and reduce nutrients losses, and/or minimize the adverse environmental impacts. Various benefits of using nanofertilizers are:

- Higher product quality with minimum remnants.
- Eco-friendly synthesis.
- Custom-made products.
- Lower-cost production, reducing the amount of fertilizers used.

Table 26.4 Advantages related to nanotech-modified formulation of conventional fertilizers

Desirable properties	Examples of nanofertilizers-enabled technologies
Controlled release formulation	The so-called smart fertilizers might become reality through transformed formulation of conventional products using nanotechnology. The nanostructured formulation could allow fertilizers to intelligently monitor nutrient release speed to fit crop uptake trends
Solubility and dispersion for mineral micronutrients	Nanosized formulation of mineral micronutrients may improve solubility and dispersion of insoluble nutrients in soil, reduce soil absorption and fixation, and increase the bioavailability
Nutrient uptake efficiency	Nanostructured formulation might increase fertilizer efficiency and uptake ratio of the soil nutrients in crop production and save fertilizer resource
Controlled release modes	Both release rate and release pattern of nutrients for water soluble fertilizers might be precisely controlled through encapsulation in envelope forms of semi-permeable membranes coated by resin-polymer, waxes, and sulfur
Effective duration of nutrient release	Nanostructured formulation can extend effective duration of nutrient supply of fertilizers into soil
Loss rate of fertilizer nutrients	Nanostructured formulation can reduce loss rate of fertilizer nutrients into soil by leaching and/or leaking

Source: modified from Cui et al. (2010)

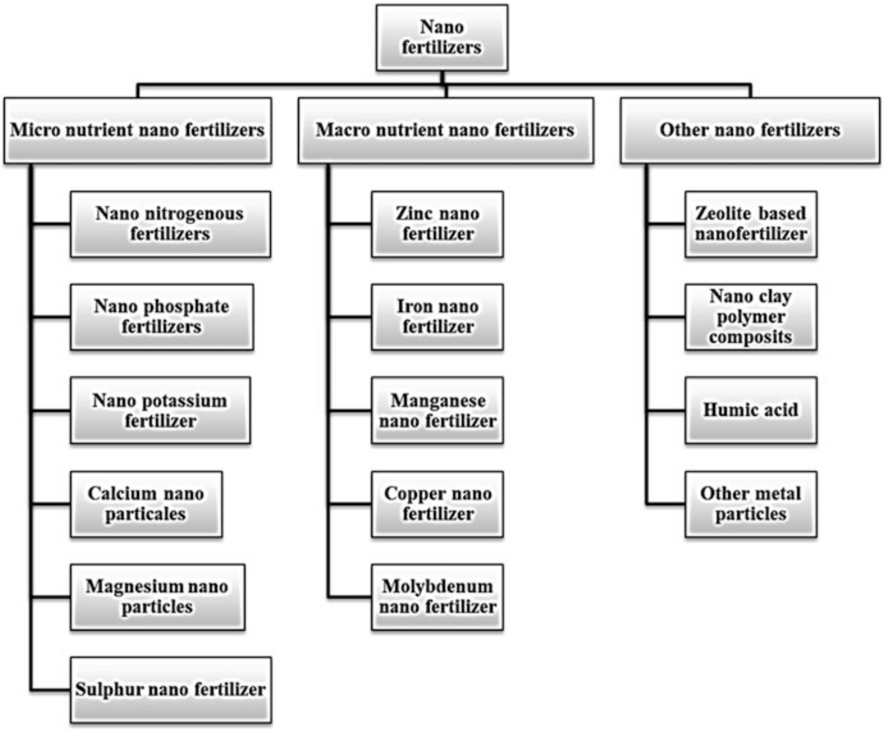

Fig. 26.2 Different types of nanofertilizers

- Less negative impacts and toxicity.
- Controlled release of plant nutrients.

Small size of the NFs facilitate its effective absorption by the plants due to the tremendous increase in the surface area (Fig. 26.3). Moreover, these have the ability to enter into the cells directly as these materials are small sized, which reduces/bypasses the energy-intensive mechanisms of their uptake/delivery into the cell. Similar to the conventional fertilizers, NFs are dissolved in the soil solution and the plants can directly take them up. However, their solubility might be more than that of related bulk solids found in the rhizosphere due to their small size. These are more efficient compared to the ordinary fertilizers, as these reduce nutrient loss due to leaching, emissions, and long-term incorporation by soil microorganisms. Moreover, controlled release NFs may also improve fertilizer use efficiency (FUE) and soil deterioration by decreasing the toxic effects associated with over application of traditional chemical fertilizers (Suman et al. 2010). There are also reports about the use of nanoencapsulated slow release fertilizers. Recently, biodegradable, polymeric chitosan NPs (~78 nm) have been used for controlled release of NPK fertilizer sources such as urea, calcium phosphate, and potassium chloride (Corradini et al.

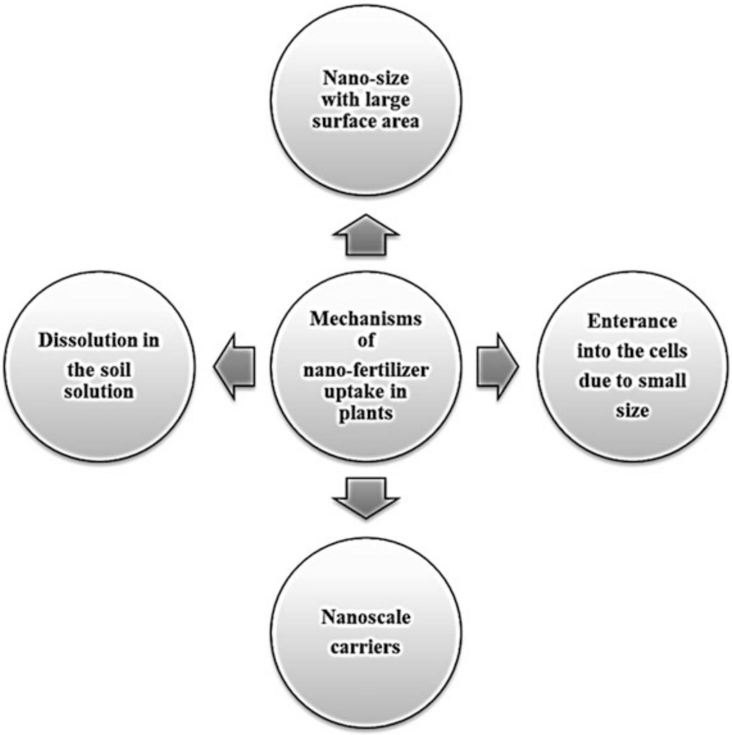

Fig. 26.3 General mechanisms employed by NFs for better uptake in plants

2010). Other NMs like kaolin and polymeric biocompatible NPs could also be utilized for this purpose (DeRosa et al. 2010).

26.3.1 Synthesis of Nanofertilizers

Nanofertilizers are synthesized by top-down (physical) or bottom-up (chemical) approaches. Top-down approach is a commonly used method. In top-down approach, the adsorbent or substrate used for synthesis of nanofertilizers such as zeolite or any other carrier is ball milled for several hours to achieve nanodimension. Usually, natural zeolite measures a range of 1000–3000 nm, and grinding using high-energy ball mill reduced the size of the particles. Manik and Subramanian (2014) reported that the ball milling of zeolite at 1, 2, 4, and 6 h had reduced the dimension 1078, 475, 398, 357, and 203 nm, respectively. The size reduction closely coincided with the increase in the respective surface area of 41, 55, 72, 83, and 110 $m^2\ g^{-1}$. This phenomenal increase in the surface area provides extensive surface for nutrient adsorption and desorption. Despite the physical method of nanoparticle synthesis is very simple, the product is heterogeneous and particles often get agglomerated. To prevent agglomeration, stabilizing agents such as polymers or surfactants are used. Synthesis, characteristics, and nutrient release capability of some nanofertilizers are presented in Table 26.5.

The studies on slow release fertilizers (SRFs) based on zeolites are limited to nutrients, which can be loaded in cationic forms such as NH^{4+} and K^{+}. However, if the nutrients are in anionic forms such as SO_4^{2-}, NO^{3-}, and PO_4^{3-}, the loading is negligible on unmodified zeolites. Therefore, it is imperative that the material should have adequate affinity for anions so that the anionic nutrients can be efficiently loaded for its use as SRFs. Anionic properties can easily be imparted on the zeolitic surface using the concept of surface modification using surfactant. Surface modification facilitates the loading of anion into the zeolite's surface by the anion exchange process. Haggerty and Bowman (1994) reported that surfactant modified zeolite (SMZ), a type of inexpensive anion exchanger has been shown to remove anionic contaminants from water. Hexadecyltrimethylammonium bromide (HDTMABr), a cationic surfactant, was used for surface modification of zeolite. It has been found that HDTMABr loading with a maximum of 200 mmol kg^{-1} corresponds to 200% of the zeolite's effective cation exchange capacity. A surfactant bilayer forms and the surface reversed to positive (Li and Bowman 1997). Li et al. (1998) revealed that SMZ has been studied extensively in the last 15 years due to its high capacity of sorption and retention of oxyanions. The surfactant molecules (HDTMABr) form bilayers on zeolite external surfaces with the lower layer held by electrostatic interaction between the negatively charged zeolite surface and the positively charged surfactant head groups, while the upper layer is bound to the lower layer by hydrophobic forces between the surfactant tail groups in both layers (Bowman 2003). Surface modified zeolite showed positive results on the retention of chromate (Krishna et al. 2001) and phosphate (Bansiwal et al. 2006). Li and Zhang (2010) reported that the loading capacity of sulfate compared to nitrate on SMZ may be attributed to the charge effect of the anions. Each HDTMABr molecule contributes one positive charge, which needs only one negative charge to balance. Sulfate is divalent and thus needs two HDTMABr molecules to neutralize. Meanwhile, the HDTMABr surface configuration is not rigid because of the surfactant tail–tail interaction. Thus, bridging two HDTMABr molecules with one sulfate may be less favored compared to 1:1 neutralization of HDTMABr by nitrate.

26.3.2 Characterization of Nanofertilizers

Synthesized nanofertilizers are to be characterized using particle size analyzer (PSA), zeta analyzer, Fourier transform infrared spectroscopy (FTI-IR), Raman spectroscopy, X-ray diffraction (XRD), scanning electron microscope (SEM), energy dispersive X-ray spectroscopy (EDAX), transmission electron microscope (TEM), and atomic force microscope (AFM) to confirm the size, shape, charge distribution, functional groups, elemental composition, and attachment. The synthesized nanofertilizers have been characterized using the set of equipment (Table 26.6). Extensive studies had been undertaken to characterize nitrogenous

Table 26.5 Synthesis, characteristics, and nutrient release from nanofertilizers

Nutrients	Adsorbent	Approach	Size	Nutrient release (h)	References
N	Zeolite	Physical	25–30 nm	1200	Subramanian and Sharmila Rahale (2013)
	Montmorillonite	Physical	35–40 nm	400	
	Zeolite	Chemical	200 nm	–	Komarneni (2010)
	Surface crosslinked superabsorbents (hydrogels)	Chemical	40–80 nm	672	Liu et al. (2006a, b)
	Zeolite	Physical	420 μm	16	Li (2003)
	Hydroxyapatite nanoparticles + *Gliricidia Sepium*	Biological	19–25 nm	1440	Kottegoda et al. (2011)
	Zeolite	Physical	60 nm	1176	Selva Preetha (2011)
	Zeolite	Chemical	7–10 nm	480	Mohanraj (2013)
	Zeolite	Physical	87 nm	1152	Manik and Subramanian (2014)
	Montmorillonite	Chemical	50 μm	240	Bortolin et al. (2013)
P	Zeolite	Physical	25–30 nm	1104	Subramanian and Sharmila Rahale (2013)
	Montmorillonite, bentonite	Physical	35–40 nm	284	
	Zeolite	Physical	60 nm	1000	Selva Preetha (2011)
	Zeolite	Chemical	2–3 μm	1080	Bansiwal et al. (2006)
K	Zeolite	Physical	25–30 nm	1176	Subramanian and Sharmila Rahale (2013)
	Montmorillonite, bentonite	Physical	35–40 nm	216	
S	Zeolite	Physical	70–93 nm	816	Thirunavukkarasu (2014)
	Zeolite	Physical	420 μm	55	Li and Zhang (2010)
	Zeolite	Physical	60 nm	1520	Selva Preetha et al. (2014)
Zn	Zeolite	Physical	25–30 nm	1176	Subramanian and Sharmila Rahale (2013)
	Montmorillonite, bentonite	Physical	35–40 nm	312	
	Nano-Zn	Chemical	35 nm	–	Nair et al. (2010)
	Nano-ZnO	Chemical	20 nm	–	Mahajan et al. (2011)
B	Zeolite	Physical	60 nm	1,500	Selva Preetha (2011)

Table 26.6 Application of different instruments in characterization of nanoparticles

Instruments	Use in characterization
Particle size analyzer (PSA)	Measure particle size of suspensions or dry powders based on different technologies, such as high definition image processing, analysis of Brownian motion, gravitational settling of the particle, and light scattering (Rayleigh and Mie scattering) of the particles
Zeta analyzer	Measure effective electric charge on the nanoparticle surface and used as an indicator of dispersion stability
Fourier transform infrared spectroscopy (FTI-IR)	Identify different functional groups that are present in a system by measuring the vibrational frequencies of the chemical bonds involved
Raman spectroscopy	The use of inelastic scattering of light falling on a substance is used for non-destructive, microscopic, chemical analysis, and imaging of materials
X-ray diffraction (XRD)	X-ray diffraction (XRD) is a nondestructive technique that provides detailed information about the crystallographic structure, chemical composition, and physical properties of materials
Scanning electron microscope (SEM)	Measure surface topography and composition
Energy dispersive X-ray spectroscopy (EDAX)	Measure elemental analysis or chemical characterization of a sample
Transmission electron microscope (TEM)	TEM is the preferred method to directly measure nanoparticle size, grain size, size distribution, and morphology
Atomic force microscope (AFM)	3D characterization of nanoparticles with sub-nanometer resolution

(Subramanian and Sharmila Rahale 2013; Mohanraj 2013; Manik and Subramanian 2014), phosphatic (Bansiwal et al. 2006; Adhikari 2011; Behnassi et al. 2011), potassic (Subramanian and Sharmila Rahale 2012), sulfatic (Selva Preetha et al. 2014; Thirunavukkarasu 2014), and zinc (Subramanian and Sharmila Rahale 2012) fertilizers.

26.4 Micronutrient Nanofertilizers

Micronutrients play an important role in many physiological functions of plants. These are required in a very small amount ($\leq$100 ppm) but have a very critical role in various plant metabolic processes. These include chloride (Cl), iron (Fe), boron (B), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), and nickel (Ni). These are applied to the plants either as Hoagland solution (Hoagland and Arnon 1950) or as foliar or applied in soil depending on crop species and also on the nutrient to be applied. These are also applied to the crop plants with composite fertilizers containing multiple macronutrients like NPK. Micronutrients present in these composites usually provide enough nutrients and cause little environmental risks. However, their availability is severely affected by small changes in pH, soil texture, and organic matter (Fageria 2009). So, it is most likely that under such circumstances, their optimum availability could be achieved through the application of NFs containing these micronutrients. A summary of the studies conducted regarding the investigation of the efficacy of each micronutrient-containing NPs is given in Table 26.7.

26.4.1 Zinc Nanofertilizer

Many researchers around the world have focused on finding the effect of ZnO-NPs on the growth and productivity of crops. Out of all the micronutrients, it is the most widely studied in plant science worldwide. For example, optimal concentration of ZnO-NPs significantly enhanced the growth and yield parameters of mung bean and chickpea (Mahajan et al. 2011). Optimal concentration of ZnO-NPs to be applied depends on the nature of the crop. With the application of 20 mg L^{-1} ZnO-NPs to mung bean plants, an increase of 42%, 41%, 98%, and 76% in root length, root biomass, shoot length, and shoot biomass, respectively, was recorded. Moreover, the application of higher doses of ZnO-NPs caused a decrease in the growth rates of mung bean and chickpea. In another greenhouse experiment, the application of ZnO-NPs at the rate of 400 and 800 mg kg^{-1} caused a significant increase in the growth and yield parameters of cucumber (*Cucumis sativus*) (Zhao et al. 2014). The results clearly showed an increase of 10% and 60% in plant root dry mass with the application of 400 and 800 mg kg^{-1}, respectively, as compared to control (without ZnO-NPs). However, the same rates caused a slight increase of 0.6% and 6% in the dry fruit weight, respectively, as compared to the control. Similarly, Lin and Xing (2007) reported a significant increase in the root elongation of germinated seeds of radish (*Raphanus sativus*) and rape (*Brassica napus*) with the application of ZnO-NPs at 2 mg L^{-1}, in comparison to control (deionized water). The authors also found a significant improvement in the growth parameters of ryegrass (*Lolium perenne*) with the application rate of 2 mg L^{-1} metallic Zn-NPs. Seed germination was improved with the application of lower concentrations of ZnO-NPs in peanut (Prasad et al. 2012), soybean (Sedghi et al. 2013), wheat (Ramesh et al. 2014), pearl millet (Tarafdar et al. 2014), tomato (Raliya et al. 2015), and onion (Raskar and Laware 2014). In another experiment, a significant improvement in *Cyamopsis tetragonoloba* plant biomass, shoot and root growth, root area, chlorophyll and protein synthesis, rhizospheric microbial population, acid phosphatase, alkaline phosphatase, and phytase activity in cluster bean rhizosphere was recorded with the application of ZnO-NPs (Raliya and Tarafdar 2013). Similarly, Helaly et al. (2014) found that ZnO-NPs supplemented with MS-media promoted somatic embryogenesis, shooting, regeneration of plantlets, and also induced proline synthesis, activity of superoxide dismutase, catalase, and peroxidase, thereby improving tolerance to biotic stress. In contrast to these studies, many researchers have reported phytotoxicity of the application of Zn-NPs in various crop plants (Mahajan et al. 2011; Lin and Xing 2007; Lee et al. 2010; López-Moreno et al. 2010). However, phytotoxicity depends on the nature of crop plants. Overall, most

Table 26.7 Nanomicronutrient fertilizers and their effects on plant growth parameters

Nutrient provided	Crop and experimental conditions	Size	Rate of application	Comments	References
Zn	*Vigna radiata* and *Cicer arientinum*, incubated 60 h in agar medium	20 nm	ZnO at 1–2000 mg L^{-1}	Growth and yield parameters in both improved	Mahajan et al. (2011)
	Cucumis sativus, 53 days greenhouse pot study	10 nm	ZnO at 400 and 800 mg kg^{-1} soil	Root dry mass, fruit starch, glutelin, and Zn contents significantly improved	Zhao et al. (2014)
	Brassica napus and *Lolium perenne*, 5 days germination	ZnO NP 20 nm and metallic Zn 35 nm	ZnO at 1–2000 mg L^{-1} applied to *Brassica napus* and metallic Zn at 1–2000 mg L^{-1} applied to *Lolium perenne*	Improved root elongation in both and Zn-NPs at levels higher than the optimum showed phytotoxicity	Lin and Xing (2007)
	Arachis hypogaea germination and field trial during 2008–2010	nZnO 25 nm	nZnO at 1000 ppm and chelated bulk zinc sulfate ($ZnSO_4$), a field experiment with nZnO applied at 15 times lower dose compared to chelated $ZnSO_4$	Promoted both seed germination and seedling vigor, early flowering, higher leaf chlorophyll content, pod yield per plant compared to chelated bulk $ZnSO_4$; in field experiment, there was higher pod yield compared to chelated $ZnSO_4$	Prasad et al. (2012)
	Glycine max L.	–	nZnO at 0, 0.5, and 1 g L^{-1}	Increased germination over control; greater radicle length and fresh weight in stressed seedling	Sedghi et al. (2013)
	Triticum aestivum L.	–	nZnO at 20–50 nm	Significantly increased chlorophyll and protein content	Ramesh et al. (2014)
	Pennisetum americanum	15–25 nm	Biosynthesized Zn-NPs sprayed at 16 L ha^{-1} after 2 weeks of germination at 10 ppm	Improved growth, physiological, biochemical, and yield parameters over control in 6-week-old plants	Tarafdar et al. (2014)
	Solanum lycopersicum L.	25 ± 3.5 nm	TiO_2- and ZnO-NPs at 0–1000 ppm	Promoted growth and development	Raliya et al. (2015)

(continued)

Table 26.7 (continued)

Nutrient provided	Crop and experimental conditions	Size	Rate of application	Comments	References
	Allium cepa	–	ZnO-NPs at 0.0, 10, 20, 30, and 40 g mL^{-1}	Low concentrations increased seed germination but decreased under higher ones	Raskar and Laware (2014)
	Cyamopsis tetragonoloba L.	–	Biosynthesized nZnO foliar sprayed at 10 ppm	Improved growth, yield, and quality parameters	Raliya and Tarafdar (2013)
	Musa acuminata in vitro cultures	–	nZn and nZnO	Somaclones accumulated more proline, chlorophyll, antioxidant enzymes activity, and developed more dry weight than the control	Helaly et al. (2014)
	Arabidopsis thaliana (mouse-ear cress)	–	nZnO at 400, 2000, and 4000 mg L^{-1}	nZnO was most phytotoxic; inhibition of seed germination depended on particle size at equivalent concentrations	Lee et al. (2010)
	Medicago sativa, *Cucumis sativus*, and *Solanum lycopersicum*	–	nZnO at 0–1600 mg L^{-1} and Zn^{2+} at 0–250 mg L^{-1}	While it decreased in Medicago sativa and Solanum lycopersicum, observed highest Zn content in alfalfa with 1600 mg L^{-1} nZnO and 250 mg L^{-1} Zn^{2+}	de la Rosa et al. (2013)
	Lolium perenne	–	nZnO and nZn^{2+}	Reduced biomass, root tips shrank, and root epidermal and cortical cells highly vacuolated/collapsed; nZnO was observed in apoplast and protoplast of the root endodermis and stele	Taran et al. (2014)
Fe	*Vigna unguiculata* subsp. *unguiculata*, foliar application, field study	–	Fe-NPs at 0.25 and 0.5 g L^{-1}	More 1000-seed weight, leaf Fe, and chlorophyll content compared to regular Fe salt	Liu et al. (2005)

	Glycine max greenhouse test 7 days, perlite medium, nutrient solution	18.9–20.3 nm	Superparamagnetic iron oxide NPs, Fe_3O_4 at 30, 45, and 60 mg L^{-1}	Chlorophyll contents increased up to 45 mg L^{-1} but decreased at 60 mg L^{-1}	Fageria (2009)
	Cucurbita pepo cultivated in vitro	–	Carbon-coated Fe-NPs	–	Malekian et al. (2011)
Mn	*Vigna radiata* 15 days in growth chamber, perlite medium, nutrient solution	20 nm	Metallic Mn at 0.05, 0.1, 0.5, and 1.0 mg L^{-1}, $MnSO_4$	Metallic Mn increased growth and physiological parameters more compared to $MnSO_4$; Mn-NPs did not show phytotoxicity	Ghafariyan et al. (2013)
Cu	*Phaseolus radiatus* and *Triticum aestivum*		nCu	The 2-day median effective concentrations for *P. radiatus* and *T. aestivum* exposed to nCu were 335 and 570 mg L^{-1}, respectively	Lee et al. (2008)
	Cucurbita pepo		Bulk and Cu-NPs and Ag-NPs were directly compared	Bulk and NP Cu were highly phytotoxic; humic acid (50 mg L^{-1}) decreased the ion content of bulk Cu solution but increased Cu^{2+} of NP solutions	Musante and White (2012)
	Lactuca sativa, 15-day germination, soil	50 nm	Metallic Cu at 130 and 600 mg kg^{-1} as Cu	Increased shoot:root ratio, total N, and organic matter at 130 mg kg^{-1}	Shah and Belozerova (2009)
	Elodea densa planch, 3-day incubation, water	30 nm	70% CuO and 30% Cu_2O at 0.025, 0.25, 0.5, 1, and 5 mg L^{-1} as Cu, $CuSO_4$	Increased photosynthesis rate but leaf Cu at <0.5 mg L^{-1} $CuSO_4$ inhibitory at all concentrations	Nekrasova et al. (2011)
Mo	*Cicer arietinum*, rhizosphere soil examination	100–250 nm	Mo at 8 mg L^{-1}, others unknown	Improved nodule number/mass, activity of antioxidant enzymes, and symbiotic bacteria	Taran et al. (2014)

of the crop plants usually require merely 0.05 mg L^{-1} soil solution. The researchers in these studies applied metallic Zn-NPs at a very high rate, ranging from 400 to 2000 mg L^{-1}, which was the main reason for their toxic effects. Even the application of Zn-NPs at 10 mg L^{-1} to ryegrass proved harmful for normal growth (Lin and Xing 2008). In another study, among cucumber, alfalfa, and tomato, the application of ZnO-NPs only enhanced seed germination of cucumber (de la Rosa et al. 2013).

26.4.2 Iron Nanofertilizer

In a greenhouse study under a hydroponic system, application of lower concentrations of Fe-NPs (30, 45, and 60 mg L^{-1}) significantly improved the chlorophyll contents of the sub-apical leaves of soybean compared to the regular application of Fe-EDTA (Ghafariyan et al. 2013). The results suggested that Fe-NPs could serve as an efficient source of Fe compared to the regular Fe-EDTA applied at $<$45 mg L^{-1} as Fe, thereby reducing the chloratic symptoms caused by its deficiency in soybean. Moreover, the uptake efficiency of Fe-NPs in the plant body was enhanced, which ultimately increased the chlorophyll contents of soybean plants. In another experiment, growth and yield parameters of black-eyed peas were significantly improved when Fe-NPs were applied as foliar at 500 mg L^{-1} (Delfani et al. 2014). Moreover, the application of Fe-NPs improved the effect of another fertilizer nutrient applied in the form of Mg-NPs. Previously, Hoagland and Arnon (1950) found that most of the plants generally require 1–5 mg L^{-1} Fe in soil solution.

26.4.3 Manganese Nanofertilizer

A hydroponic culture experiment was conducted to find out the comparative efficacy of Mn-NPs and commonly used Mn-salt, i.e., $MnSO_4$, on the growth and yield parameters of mung bean (Pradhan et al. 2013). Both were applied at 0.05, 0.1, 0.5, and 1.0 mg L^{-1}. The results showed that application of Mn-NPs at 0.05 mg L^{-1} significantly improved growth and yield parameters compared to the control with no Mn applied. At higher doses, Mn-NPs did not show toxicity to the bean plants, while $MnSO_4$ applied at 1 mg L^{-1} showed toxic effects like necrotic leaves, brown roots, and gradual disappearance of the rootlet after 15 days of treatment. Moreover, greater oxygen evolution and photophosphorylation in Mn-NP-treated chloroplasts was noted compared to the control. Greater oxygen evolution was caused by enhanced splitting of water in the oxygen-evolving center located in the chloroplast. The authors concluded that Mn-NPs could serve as a potential modulator of photochemistry in the agriculture sector.

26.4.4 Copper Nanofertilizer

Previously, it has been clearly found that the application rate of Cu-NPs at Cu 0.02 mg L^{-1} in Hoagland solution is optimum for normal growth and yield of crops. Scientists around the world have found toxic effects of the application of Cu-NPs, as they have applied them at higher rates than required (Lee et al. 2008; Musante and White 2012). They found that Cu-NPs applied at the rate of 200–1000 mg L^{-1} caused toxic effects on seedling growth of mung bean, wheat, and yellow squash. Similarly, reduced biomass of zucchini by 90% compared to that of the control (without Cu) after the seedlings were incubated in Hoagland solution for 14 days was recorded with the application of metallic Cu-NPs at 1000 mg L^{-1}. However, researchers like Shah and Belozerova (2009) recorded a significant increase of 40% and 91% in 15-day lettuce seedling growth rate with the application of Cu-NPs at 130 and 600 mg kg^{-1}, respectively. Similarly, a 35% increase in photosynthetic rate of waterweed was recorded in a 3-day incubation study using a low concentration of Cu-NPs applied at $\leq$0.25 mg L^{-1} (Nekrasova et al. 2011).

26.4.5 Molybdenum Nanofertilizer

Molybdenum is essential for legumes as it is involved in biological nitrogen fixation (BNF), being the component part of nitrogenase enzyme. For normal metabolism of crop plants the concentration of soil solution Mo should be $\approx$0.01 mg L^{-1}. Taran et al. (2014) conducted a pot experiment using different combinations of N-fixing bacteria and Mo-NPs (water, Mo-NPs, microbial inoculation with nitrogen-fixing bacteria, and a combination of the microbes and Mo-NPs). The control was treated with distilled water. Chickpea seeds were soaked in each of the treatments for 1–2 h. The results clearly showed that the combined application of microbes and Mo-NPs significantly improved the microbiological properties of the rhizosphere, including all groups of agronomically important microbes. The same combination significantly improved the root number, nodule number per plant, and nodule mass per plant compared to control.

26.5 Risk of Nanoparticle Application on Environment

Application of nanomaterials in agriculture is not always beneficial. It has number of negative effects on soil, plant, and aquatic life and most importantly human because of long food chain and easy motion of nanoparticles. Study of behavior of nanoparticles at different sizes with different concentrations in soil, plant, and water is as under:

26.5.1 Risk of Nanoparticle Application on Soil

Soil is prima facie receiver of fertilizers with nanoparticles. There is harmful chemical reactions and contamination by these nanoparticles to soil ecosystem and change in soil structure due to their large surface area and Brownian motion. Nanoparticles used through fertilizers could be harmful to soil biota and fertility (Ranallo 2013). They affect microbes, microfauna of soil, and digestive system of earthworm. An adverse effect of nanoparticles on soil health is presented in Table 26.8.

The potential harmful effects of nanoparticles Ag, TiO_2, ZnO, CeO_2, Fe_3O_4 include reduction in growth, fertility, survival, and increased mortality of earthworm and soil bacteria. Size is the main factor for ecotoxicity. To find out the relationship between size and toxicity, Roh et al. (2010) have initiated a study with TiO_2 and CeO_2 nanoparticle on *Caenorhabditis elegans*. It is a free-living, transparent nematode, about 1 mm in length that lives in temperate soil environments. They found that smaller size of TiO_2 (7 nm) and CeO_2 (15 nm) nanoparticles are more toxic compared to larger size (TiO_2 of 20 nm and CeO_2 of 45 nm). It has been found that higher doses of ZnO nanoparticle become toxic for soil (Hu et al. 2010). Whereas, the amount of ZnO in the soil is increased from 1 g kg^{-1} to 5 g kg^{-1}, ZnO nanoparticles bioaccumulate within the earthworm and cause DNA damage.

26.5.2 Risk of Nanoparticle Application on Plant

Toxicity of nanoparticles depends upon various factors like plant species, size, and concentration of nanoparticles in different stages of crop. Toxic effect of nanoparticles also depends upon their composition and size. Small sized nanoparticles are more reactive and toxic compared to large sized and affect the respiration or photosynthesis process (Navarro et al. 2008). Hund-Rinke and Simon (2006) worked on different sizes of photocatalytic active TiO_2 nanoparticles and its ecotoxic effect on algae (EC50: 44 mg L^{-1}) and daphnids with maximum concentration of 50 mg L^{-1} and found that ecotoxicity of nanomaterials depends upon nature of particles. Toxicity found in algae is more than daphnids. Lin and Xing (2007) worked on phytotoxicity of nanomaterials. They used MWCNT, Al, Al_2O_3, Zn, and ZnO in their experiment on radish, rape, ryegrass, lettuce, corn, and cucumber and found that seed germination of corn and ryegrass is affected by nanoscale ZnO and Zn, respectively. Aluminum oxide (Al_2O_3) nanoparticles showed phytotoxicity only on corn, which reduced the root elongation by 35%. Aluminum (Al) improved root growth of rape and radish and inhibited root elongation of ryegrass and lettuce but had no effect on cucumber. Some of the toxicological studies on the effect of nanomaterials are presented in Table 26.9.

The level of toxicity in plants due to nanoparticles is in direct relation with size and nature of the particles. Zinc oxide (ZnO) nanoparticles easily dissolve in soil and uptake by plant and TiO_2 nanoparticles accumulate in soil and retain for long time and stick with the cell wall of wheat plant. Both reduced the biomass of wheat crop

Table 26.8 Adverse effects of nanoparticles on soil health

Nanoparticle	Size (nm)	Effect	References
Ag	9–21	The activity of nitrifying bacteria was reduced by 50%	Okkyoung and Zhiqiang (2008)
C_{60} fullerene	50	Fast growing bacteria and protozoa were reduced by 20–30%	Johansen et al. (2008)
Ag, CeO_2, and TiO_2	7–45	Growth (9–21%), fertility (11–28%), and survival (20–30%) of Caenorhabditis elegans (species of nematode) were reduced	Roh et al. (2009, 2010)
TiO_2 and ZnO	10–20	Traces of ZnO (~50 μg g^{-1} weight) and TiO_2 (~32 μg g^{-1} weight) were found inside the earthworm	Hu et al. (2010)
ZnO, Zn, and Zn^{2+}	50	Soil enzymes (dehydrogenase, phosphatase, and β-glucosidase) were reduced by 17–80%	Kim et al. (2011)
Ag	10	Culturability of beneficial soil bacterium *Pseudomonas chlororaphis* O_6 was reduced	Calder et al. (2012)
Zero-valent iron (nZVI)	20–100	Mortality of *Eisenia fetida* and *Lumbricus rubellus* species of earthworm was 100% at 750 mg kg^{-1}	El-Temsah and Joner (2012)
CeO_2, Fe_3O_4, and SnO_2	50–105 (CeO_2), 20–30 (Fe_3O_4), and 61(SnO_2)	Microbial stress was noticed	Antisari et al. (2013)
Cr_2O_3, CuO, Ni, and ZnO	<100	The activity of enzyme (60%), dehydrogenase (~75%), and urease (44%) was reduced	Jośko et al. (2014)

(Du et al. 2011). Phytotoxicity was studied by Mazumdar and Ahmed (2011) on rice crop. They found that silver nanoparticle accumulated inside the root cell and damage the cell walls during penetration of particles due to complex mechanism and small size of particles, it damaged the external and internal portion of cell wall. The other factor for plant toxicity is the concentration of nanoparticle because a nanoparticle of same size in different concentration changes its chemical properties. Zinc oxide nanoparticle showed great toxicity in different concentrations (Boonyanitipong et al. 2011). They found that ZnO starts showing adverse effect on rice plant from 100 mg L^{-1} and fully inhabits root growth and biomass at 500–1000 mg L^{-1} concentration.

26.5.3 Risk of Nanoparticle Application on Water

The nanoparticles can easily be released in water body or air and uptake by living organisms, create toxic effect for human, animals, and also for aquatic life. Titanium

Table 26.9 Toxicological effect of nanoparticles on plant

Nanoparticle	Size (nm)	Crop	Adverse effect	References
TiO_2 and ZnO	20–100 (TiO_2) and 40–50 (ZnO)	Wheat (*Triticum aes*tivum)	Wheat biomass was reduced by 7.6% due to TiO_2. No significant result due to ZnO	Du et al. (2011)
ZnO and TiO_2	–	Rice (*Oryza sativa* L.)	75% reduction in root as concentration of ZnO increased from 10 to 1000 mg L^{-1}. No significant reduction with TiO_2	Boonyanitipong et al. (2011)
TiO_2	<100	Corn (*Zea mays*)	Aberration index increased from 0.5% to 2.5% with control and 4% concentration, respectively. Inhibits root elongation by 34%	Castiglione et al. (2011)
Au	25	Rice (*Oryza sativa* L.)	Damage of internal and external cell wall of root due to deposition of Au through xylem	Mazumdar and Ahmed (2011)
Aluminum oxide (Al_2O_3)	–	Tobacco (*Nicotiana tabacum*)	As concentration of Al_2O_3 increased as 0–1%, the average root length, biomass per seedling, and germination rate significantly decreased as 93%, 83%, and 2%, respectively	Burklew et al. (2012)
ZnO and Fe-ZnO	18.4 (ZnO) and 13.4 (Fe-ZnO)	Green pea (*Pisum sativum* L.)	Chlorophyll and ROS (reactive oxygen species) production were reduced by 27% and 50%, respectively	Mukherjee et al. (2014)

oxide (TiO_2) reduced the light to entrap the algal cell and thus reduce the growth (Sharma 2009). The toxicity study of Ag, Cu, Al, Ni, TiO_2, and Co nanomaterials on algal species, zebrafish, and daphnids revealed that Ag and Cu nanoparticles cause toxicity to all organisms (Griffitt et al. 2008) and the metal form is less toxic than soluble form of nanoparticles. Table 26.10 describes the aquatic toxicity of use of nanomaterials release in surface water body. It has been proved from different studies that nanoparticles like Ag, Cu, Al, Ni, and TiO_2 cause unrecoverable toxic effect on aquatic ecosystem. Silver, iron oxide, and copper nanoparticle adversely affected health of zebrafish. It enhances mortality, hatching, and reduces heartbeat and survival rate affect normal development (Asharani et al. 2008; Griffitt et al. 2007; Zhu et al. 2012). Therefore, the level of nanotoxicity in soil, plant, and water mainly depends on the composition, size (<20 nm), and concentration (>100 ppm) of the nanoparticle.

Table 26.10 Adverse effects of nanoparticles on aquatic species

Nanoparticle	Size (nm)	Aquatic species	Effect	References
Fullerene (nC_{60})	10–200	Daphnia	Mortality was increased by 40% and offspring production was reduced by 50%	Oberdörster et al. (2006)
Cu	80	Zebrafish	NKA (Na/K ATPase) activity was reduced by 88%	Griffitt et al. (2007)
TiO_2	21	Rainbow trout	Glutathione level was reduced by 65%	Federici et al. (2007)
Ag	5–10	Zebrafish	Heartbeat (150–50 beat min^{-1}) was decreased from 150 to 50 beat min^{-1} and mortality rate was 10%	Asharani et al. (2008)
TiO_2	10–100	Marine phytoplankton	Toxic to the aquatic life in sunlight	Miller et al. (2012)
Ag	18	Freshwater fish *Cyprinus carpio*	Mortality was 100% at 1 ppm NP's concentration	Hedayati et al. (2012)
FeO	30	Zebrafish	About 75% of fishes were killed at high concentration (50 mg L^{-1}) of NP	Zhu et al. (2012)

26.5.4 Risk of Nanoparticle Application on Human Health

The emerging field of nanotechnology has created an interest on human health risk associated with nanoparticles. These particles create new challenge for researchers to understand and find risk associated with human health. Exposure of these materials occurs through inhalation, ingestion, and dermal exposure during synthesis, manufacturing, and application of these nanomaterials. Table 26.11 shows the adverse effects of nanomaterials on human health.

The most common way of exposure is inhalation of airborne nanoparticles. Greatest emission risk occurs in the manufacturing process with poor filtering and ventilation system (AFSSET 2006). Factors that affect inhaled dose are particle geometry and physiochemical properties, lung morphology, respiration physiology, and environmental condition (Shade and Georgopoulos 2007). Nanoparticles deposit in respiratory traces after inhalation increases the total deposition fraction (TDF) in the lungs with decrease in particle sizes. Nanoparticles can also be taken-up in the brain through the olfactory epithelium (Borm et al. 2006; Jaques and Kim 2000). Ultrafine airborne particles may increase respiratory and cardiovascular morbidity and mortality (Shade and Georgopoulos 2007).

Ingestion is another source of entry of nanoparticles into human body. The nanoparticles entered through gastrointestinal tract directly through intentional ingestion or indirectly via water, food, animal food, and fish (Bergin and Witzmann 2013). Mucociliary escalators may be excreted as inhaled particles or absorbed into the gastrointestinal tract; however, absorption is dependent on particle size and physicochemical characteristics (Hagens et al. 2007). Jani et al. (1990) found that

Table 26.11 Adverse effects of nanoparticles on human health

Nanoparticle	Size (nm)	Body part	Effect	References
MWCN and carbon nanofibers (CNFs)	20 (MWCN) and 150 (CNFs)	In vitro on lung tumor cells	MWCN and CNFs reduced the living cells by 33% and 58%, respectively	Magrez et al. (2006)
TiO_2, Ag, Al, Zn, and Ni	–	Alveolar epithelial cells and apoptotic damage	Cell damage was observed in all cases	Park et al. (2007)
ZnO	30	Epidermal cells	Glutathione (51–59%), catalase (55–64%), and superoxide dismutase (72–75%) were reduced	Sharma et al. (2009)
Ag	<10	Hepatoma cells	Cytotoxicity (oxidative stress) was noted	Kim et al. (2009)
CuO	<50	Lung epithelial cells A549	Cell viability was decreased by 40%	Moschini et al. (2010)
TiO_2	1–200	Mammalian cell	Reactive oxygen species production, cytokines level, apoptosis, and genotoxicity were increased and cell viability and proliferation were reduced	Iavicoli et al. (2011)
Cadmium sulfide (CdS)	~3	*Escherichia coli* and HeLa cells	Oxidative stress in both *Escherichia coli* and HeLa cells. Reduced growth of *E. coli* by 50%	Hossain and Mukherjee (2013)
Ag	10–80	Lung cell (via inhalation)	Cell viability was decreased by 20–40%, oxidative stress in cells	Nguyen et al. (2013)
Ag	10–50	–	The Ag particles of size 10 nm were found more cytotoxic than other size	Gliga et al. (2014)
Cu	23.5	Nerve cells and astrocyte cell	Central nervous system was damaged	Bai et al. (2014)

particle size less or equal to 50 nm had more uptake or absorbed across gastrointestinal tract and can be passed to the liver, spleen, blood, and bone marrow by the momentary lymph supply and nodes. Plants have more resistance to prevent translocation of nanoparticles than mammalian barriers (Birbaum et al. 2010).

Dermal exposure is an import route to absorb nanoparticles via the skin. Skin constitutes about 10% of the body's weight and acts as a buffer against external impurities, as well as shielding, preserving homeostasis, digestion, synthesis, and deposition functions (Crosera et al. 2009). Penetration of nanoparticles depends upon physicochemical characteristics of nanoparticles and medical condition of skin such as eczema, dermatitis, and skin irritation. Absorption between epidermis and dermis or permeability increases in damage skin (Nielsen et al. 2007). Dermal exposure of small size nanoparticles lower than 10 nm is more dangerous. This size of particles may cause erythema, edema, and eschar formation. Further larger size particles cannot penetrate into the skin from transappendageal routes (Gautam et al. 2011).

Thus, it has been established that nanoparticles adversely affect human health and the potential routing could be through inhalation, ingestion, and dermal exposure. It is understood that the nanoparticles show significant health complications in human when exposed to the size of particles less than 50 nm.

26.5.5 Asian Prospects of Micronutrient Nanofertilizer

Nanotechnology is considered as one of the key technologies in the twenty-first century that promises to advance traditional agricultural practices and offers sustainable development by improving the management and conservation tactics with reduced waste of agricultural inputs (Dubey and Mailapalli 2016; Shang et al. 2019). In 2018, both public and private sectors of worldwide had invested about US $1055.1 million on nanotechnology market which is projected to reach $2231.4 million by 2025. The exponential growth of global investment in nanotechnology research closely coincides with the number of patents relating to nanoproducts. Recent statistics suggests that 88% of the patents are generated from just seven countries comprising US, China, Germany, France, South Korea, Switzerland, and Japan (Subramanian and Tarafdar 2011). The Government of India is currently spending Rs.1000 crores under Nano Science and Technology Mission (Nano Mission) during the Eleventh Five-year Plan period to promote research and development in all flourishing sectors of nanotechnology, and agriculture is one of them. Within the sphere of agricultural sciences, nanotechnology application in relation to soil and crop management is in its nascent stage and over the next few years it is expected to grow exponentially.

Fertilizers play a pivotal role in agricultural production. It has been unequivocally demonstrated that fertilizer contributes to the tune of 35–40% of the productivity of any crops. Without the fertilizer input, it is hardly possible to sustain agricultural productivity of any country. Thus, attempts are being made to synthesize nanofertilizers in order to regulate the release of nutrients demand of crops and overcome the uncertainty of crop production sector with limited natural resources (Godfray et al. 2010). Based on their actions, nanofertilizer could be classified as control or slow release fertilizers, control loss fertilizers, magnetic fertilizers, nanocomposite fertilizers as combined nanodevice to supply wide range of macro- and micronutrients in desirable properties (Panpatte et al. 2016; Lateef et al. 2016). A very few nanofertilizer formulations have been synthesized in China, Taiwan, India, Germany, and the USA and are being tested under laboratory conditions. Liu et al. (2006a, b) an associate from Chinese Academy of Agricultural Sciences (CAAS) have shown that nanocomposites containing organic polymer intercalated in the layers of kaolinite clays can be used as a cementing materials to regulate the release of nutrients from conventional fertilizers. This process increases the nutrient use efficiencies, besides preventing environmental hazard. Bansiwal et al. (2006) reported the use of surface modified zeolite as a carrier of slow release phosphatic fertilizer for the first time in India.

As a promising interdisciplinary research field, nanotechnology has aroused its enormity in agriculture. Micronutrients like zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), boron (B), chlorine (Cl), molybdenum (Mo) also play an integral role in steady increase of crop productivity. However, numerous factors, such as soil pH, cation exchange capacity, soil texture, calcium carbonate content, water content, etc. stimulate their deficiencies in crop production with extensive farming practice (Ghormade et al. 2011). The deficiency of micronutrients decreases not only the productivity of crops, but also affects human health through the consumption of micronutrient-deficient foods (Swaminathan et al. 2013; Monreal et al. 2016). In contrast, the supplementation of nanoformulated or nanoentrapped micronutrients for the slow or controlled release of nutrients would stimulate the uptake process by plants, promote the growth and productivity of crops, and contribute to maintaining soil health as well (Peteu et al. 2010). Although the exact mechanism behind promotion of plant growth and enriched quality is not clear, it may be at least partially explained by the potentialities of nanomaterials to absorb more nutrients and water that in turn helps to enhance the vigor of root systems with increased enzymatic activity (Dubey and Mailapalli 2016; Shojaei et al. 2019). Therefore, the developing countries of Asia come forward to adopt these high potential technologies to ameliorate micronutrient deficiency in crop production and secure the nutritional security to the human being. The government of Myanmar is the first to undertake a program to include micronutrient nanofertilizers in their national fertilizer regimen. Later on, several other Asian countries like, India, Taiwan, Thailand, Malaysia, Iran also approved to commercialize the micronutrient nanofertilizers and Table 26.12 shows some approved micronutrient nanofertilizers currently used in these countries (Dimkpa and Bindraban 2017; Prasad et al. 2017; Elemike et al. 2019).

Nanoform of micronutrients improves their bioavailability to the plants and shows a significant improvement in plant growth and nutrition quality and some recent advancement in micronutrient nanofertilizer research in Asian countries is summarized in Table 26.13. Among the various micronutrients, Zn is the most important one, as it requires for structural component or regulatory co-factor for various enzymes and proteins in plants (Noreen et al. 2018). The foliar application of Zn and B nanofertilizers at 636 and 34 mg tree^{-1}, respectively, increased fruit yield by 30% in pomegranate trees (Khot et al. 2012). Similarly, foliar application of nano Zn and B fertilizers was found to increase fruit yield and quality, including 4.4–7.6% increases in total soluble solids (TSS), 9.5–29.1% decreases in titratable acidity (TA), 20.6–46.1% increases in maturity index, and 0.28–0.62 pH unit increases in juice pH on pomegranate without affecting any physical fruit characteristics (Davarpanah et al. 2016). Cucumber seedlings grown in nutrient solution including rubber type nanomaterial as a Zn source increased shoot and fruit yield compared

Table 26.12 List of various micronutrients nanofertilizer products available in market

Country	Nanofertilizer	Constituents	Manufacturer
India	Nano micro nutrient (eco star)	Zn, 6%; B, 2%; Cu, 1%; Fe, 6%; EDTA Mo, 0.05%; Mn, 5%; AMINOS, 5%	Shan Maw Myae Trading Co. Ltd.
	Nano fertilizer (eco star)	N, 8.2%; K_2O, 2.3%; organic matter, 75.9%; C:N, 5.4	Shan Maw Myae Trading Co. Ltd.
	Nano green	Extracts of corn, grain, soybeans, potatoes, coconut, and palm	Nano Green Sciences Inc.
	Nano N/P/K/S/Mg/Zn	Concentration 500 ppm N/P/K/S/ Mg/Zn	Kanak Biotech
	IFFCO Nano N/Zn/Cu	–	Indian Farmers Fertiliser Cooperative (IFFCO)
	NanoMax-NPK/ NanoMax-Potash/ NanoMax-Cal/ NanoMax-Zinc	Multiple organic acids chelated with major nutrients, amino acids, organic carbon, organic micronutrients/trace elements, vitamins, and probiotic	JU Agri Sciences Pvt. Ltd
	TAG Nano NPK	Proteino-lacto-gluconate formulation, formulated with organic and chelated micronutrients, vitamins, probiotics, seaweed extracts, humic acid besides N, P, and K	Tropical AgroSystem Pvt. Ltd.
	TAG nano phos	Proteino-lacto-gluconate based P in nanoform	
	TAG nano potash	Proteino-lacto-gluconate based K in nanoform	
	TAG nano cal	Proteino-lacto-gluconate formulation, containing bio-available Ca, Mg, and S	
	TAG nano zinc	Proteino-lacto-gluconate based Zn in nanoform	
	Nanomol (S) micronutrient		Alert Biotech
	Nanomol (F) micronutrient	Contains Fe, Mn, Zn, Cu, Mo, and B	
	Nano zinc	Contains 21% Zn	
	Nano bor	Contains 20% B	
	Nano ferrous		
	Nanomag	Contains 9.6% Mg	
Malaysia	PPC nano	M protein, 19.6%; Na_2O, 0.3%; K_2O, 2.1%; $(NH_4)_2SO_4$, 1.7%; diluent, 76%	WAI International Development Co. Ltd.

(continued)

Table 26.12 (continued)

Country	Nanofertilizer	Constituents	Manufacturer
Iran	Biozar nano-fertilizer	Combination of organic materials, micronutrients, and macromolecules	Fanavar Nano-Pazhoohesh Markazi Company
Taiwan	Nano ultra-fertilizer	Organic matter, 5.5%; total N, 10%; total P_2O_5, 9%; total K_2O, 14%; AC-P_2O_5, 8%; CA-K_2O, 14%; CA-MgO, 3%	SMTET Eco-technologies Co., Ltd.
	Nano organic compound fertilizer	Organic matter, 41%; total N, 11%; total P_2O_5, 10%; total K_2O, 17%; water soluble MgO, 2%	Lazuriton Nano Biotechnology Co., Ltd.
	Nano high nitrogen Compound fertilizer	Total N, 26.7%; total P_2O_5, 17.8%; total K_2O, 11.5%	
	Nano low nitrogen High phosphorus high potassium compound fertilizer	Total N, 6.8%; total P_2O_5, 29.5%; total K_2O, 23.4%; water soluble MgO, 0.4%	
	Nano High phosphorus High potassium compound fertilizer	Total N, 2.4%; total P_2O_5, 19.9%; total K_2O, 44.2%; water soluble MgO, 1.2%	
	Nano organic fertilizer	Organic matter, 87.6%; total N, 4.8%; total P_2O_5, 2.6%; total K_2O, 2.5%	
Thailand	Plant nutrition powder (green nano)	N, 0.5%; P_2O_5, 0.7%; K_2O, 3.9%; Ca, 2.0%; Mg, 0.2%; S, 0.8%; Fe, 1.0%; Mn, 49 ppm; Cu, 17 ppm; Zn, 12 ppm	Green Organic World Co., Ltd.
	Supplementary powder (the best nano)	N, 0.5%; P_2O_5, 0.7%; K_2O, 3.9%; Ca, 2.0%; Mg, 0.2%; S, 0.75%; Fe, 0.03%; Mn, 0.004%; Cu, 0.007%; Zn, 0.004%	The Best International Network Co. Ltd.
	Hero super nano	N, 0.7%; P_2O_5, 2.3%; K_2O, 8.9%; Ca, 0.5%; Mg, 0.2%; S, 0.4%; pH 12.08	World Connect Plus Myanmar Co. Ltd.
	Nano capsule (the best)	N, 0.5%; P_2O_5, 0.7%; K_2O, 3.9%; Ca, 2.0%; Mg, 0.2%; S, 0.8%; Fe, 2.0%; Mn, 0.004%; Cu, 0.007%; Zn, 0.004%	The Best International Network Co. Ltd.

with those grown in commercial $ZnSO_4$ fertilizer (Mattiello et al. 2015). Application of Zn nanoparticles in pearl millet significantly enhanced grain yield by 38%, which was also associated with an improvement of 15% in shoot length, 4% in root length, 24% in root area, 24% in chlorophyll content, 39% in total soluble leaf protein, and 12% in plant dry biomass compared to the control in a period of 6 weeks (Moghaddasi et al. 2017). It was also observed a considerable yield increase using Zn nanoparticles as a nutrient source in rice, maize, wheat, potato, sugarcane, and

Table 26.13 Indicative list of beneficial effects of micronutrients nanofertilizer application in various agro-climatic zones of the Asia

Nanofertilizer	Crops	Amount	Benefits	Reference
Zn	Ryegrass	1–2000 ppm	Root elongation	Lin and Xing (2008)
	Cucumber	1000 mg kg^{-1}	Root tip deformation and growth inhibition	Zhao et al. (2014)
	Garden pea	500 mg kg^{-1}	Decreased chlorophyll and H_2O_2 contents	Nair and Chung (2015)
	Spinach	1000 mg L^{-1}	Growth reduction	Zheng et al. (2005)
	Tomato, eggplant	1 mg mL^{-1}	Reduced fungal disease	Khan and Siddiqui (2018)
	Chili pepper	100, 200, 500 ppm	Improved germination	Tantawy et al. (2015)
	Coriander	0–400 mg kg^{-1}	Improved pigment contents and defense responses	Ahmed et al. (2018a, b)
	Onion	5, 10, 20 mg L^{-1}	Inhibition of root growth	
ZnO	Mung bean and chickpea	1–2000 ppm	Plant growth increased at 20 ppm in mung bean and in check pea at 1 ppm	Mahajan et al. (2011)
	Cucumber	400–800 ppm	Root dry weight and fruit gluten increased	Lin and Xing (2007)
	Rape seed	1–2000 ppm	Root elongation	
	Peanut	1000 ppm	34% increment in pod yield per plant	Prasad et al. (2012)
	Chickpea	1.5 ppm	Improved shoot dry weight and antioxidant activity	Burman et al. (2013)
	Maize	10 ppm	Improved plant height and dry weight	Adhikari et al. (2015)
	Cluster bean	10 ppm	Improvement in plant growth and nutrient content	Raliya and Tarafdar et al. (2013)
	Arabica coffee	10 mg L^{-1}	Enhanced growth, biomass accumulation, and net photosynthesis	Rossi et al. (2019)
	Wheat	20 mg L^{-1}	Increased grain yield and biomass accumulation	Du et al. (2019)
	Guar	10 mg L^{-1}	Improved plant growth, biomass accumulation, and nutrient content	Raliya and Tarafdar (2013)
	Tobacco	0.2 μM and 1 μM	Positively affected growth physiology, increased metabolites, enzymatic activities, and anatomical properties of plants	Tirani et al. (2019)

(continued)

Table 26.13 (continued)

Nanofertilizer	Crops	Amount	Benefits	Reference
S-NS, ZnO-NS	Mung bean	–	Increased dry weight, increased leaf area	Pradhan et al. (2013)
Nano-ZnCuFeO FeO-NS, ZnO-NS	Mung bean	–	Increased root and shoot length, increased accumulation of biomass	Dhoke et al. (2013)
Fe	Cucumber	50, 500, and 2000 mg L^{-1}	Dose-dependent effects on biomass and antioxidant enzymes	Moghaddasi et al. (2017)
	Lettuce	10, 20 mg L^{-1}	Reduced growth and chlorophyll contents and increased antioxidant enzyme activities	Trujillo-Reyes et al. (2014)
	Garden pea	30–60 ppm	Improved seed mass and chlorophyll content	Giorgetti et al. (2019)
Fe/SiO_2	Barley and maize	0–25 ppm	Improved mean germination time	Najafi Disfani et al. (2017)
	Groundnut and maize	15 mg kg^{-1}	Enhanced plant growth and biomass accumulation	Disfani et al. (2017)
FeO	Soybean	30–60 ppm	Chlorophyll increased	Ghafariyan et al. (2013)
FeS_2	Daucus, mustard, and sesame	80–100 µg mL^{-1}	Increased germination and crop yield	Srivastava et al. (2014) Das et al. (2016)
Cu	Lettuce	130–600 ppm	Shoot and root length increased	Shah and Belozerova (2009)
	Squash	0, 100, 500 mg L^{-1}	Higher ionic Cu found in media amended with bulk Cu than with nCu	Musante and White (2012)
	Lettuce	130, 660 mg kg^{-1}	Increased shoot/root length ratio	Hong et al. (2015)
	Lettuce	0, 10, 20 mg L^{-1}	Negative effects on nutrient content, dry biomass, water content, and seedlings growth	Trujillo-Reyes et al. (2014)
	Cucumber	0–1000 mg L^{-1}	Reduced growth and increased antioxidant enzymes	Kim et al. (2012)
	Radish, grasses	10–1000 mg L^{-1}	DNA damage, growth inhibition	Atha et al. (2012)
	Tomato	50–500 mg L^{-1}	Improved fruit firmness and antioxidant content	Ahmed et al. (2018a, b)
	Cilantro	0, 20, 80 mg kg^{-1}	Reduced germination and shoot elongation	Zuverza-Mena et al. (2015)

(continued)

Table 26.13 (continued)

Nanofertilizer	Crops	Amount	Benefits	Reference
	Bean	100, 250, 500 ppm	Growth inhibition and nutrition imbalance	Alsaeedi et al. (2017)
	Garden pea	100–500 mg L^{-1}	Reduced plant growth and enhanced ROS production and lipid peroxidation	Tripathi et al. (2017)
CuO	Maize	10 ppm	51% increase in plant growth	Adhikari et al. (2016)
	Spinach	200 mg kg^{-1}	Improved photosynthesis and biomass production	Wang et al. (2019)
Mn	Mung bean	0.05–1 ppm	Shoot length, chlorophyll content, and the photosynthesis rate increased	Pradhan et al. (2013)
	Rice	–	Improved Zn uptake 5.66 mg $hill^{-1}$	Yuvaraj and Subramanian (2015)
Mo	Chickpea	8 ppm	Plant mass and number of modules increased	Taran et al. (2014)

sunflower (Monreal et al. 2016; Chhipa 2017). Under Zn deficient soil, application of nano ZnO at low doses positively influences the growth and physiological responses, such as shoot and root elongation, the fresh dry weight, and photosynthesis in many plant species compared to the control (Ali et al. 2019; Asl et al. 2019). Kale and Gawade (2016) reported that application of nano ZnO with other fertilizer in Zn deficient soil not only promotes nutrient use efficiency but also increases barley productivity by 91% compared to the control. Nanoparticles of ZnO showed a significant improvement in biomass, shoot length, root, chlorophyll and protein content, and phosphatase enzyme activity in *Vigna radiate*, *Cicer arietinum*, *Cucumis sativus*, *Raphanus sativus*, *Brassica napus,* and *Cyamopsis tetragonoloba* (Lin and Xing 2007; Mahajan et al. 2011; Zhao et al. 2013; Raliya and Tarafdar 2013).

Iron is also an important nutrient required by plants in minute quantities for maintaining proper growth and development (Palmqvist et al. 2017). Delfani et al. (2014) reported that use of nano Fe on blacked eyed pea recorded 10% increment in chlorophyll content in leaves. In *Glycine max* chlorophyll content was increased significantly by nano Fe application at 30–60 mg kg^{-1} (Ghafariyan et al. 2013). Disfani et al. (2017) also found that Fe/SiO_2 nanomaterials have significant potential to improve seed germination in barley and maize. Application of 50 mg L^{-1} nano FeO in *Citrus maxima* plants significantly improved the chlorophyll contents and root activity by 23% and 24%, respectively, compared to controls (Sharma 2006). Yousefzadeh and Sabaghnia (2016) demonstrated that the application of nano Fe fertilizer not only increased the agronomic traits of *Dracocephalum moldavica* with sowing density, but also improved essential oil contents of plants. Elfeky et al.

(2013) found that foliar application of nano Fe_3O_4 could significantly enhance total chlorophyll, total carbohydrate, essential oil levels, iron content, plant height, branches per plant, leaves per plant, fresh weight, and dry weight of *Ocimum basilicum* plants compared to that of soil application. Disfani et al. (2017) demonstrated that 15 mg kg^{-1} of nano Fe and SiO_2 increased shoot length of barley and maize seedlings about 8.25% and 20.8%, respectively.

Application of nano Cu improved photosynthesis in *Elodea desaplanch* by 35% at low concentration (Nekrasova et al. 2011) and seeding growth up to 40% in lettuce (Shah and Belozerova 2009). Spray of nano Mn on *Vigna radiata* increased 52% root length, 38% shoot length 71% rootlet, and 38% biomass at 0.05 mg kg^{-1} concentration in comparison with bulk $MnSO_4$ (Pradhan et al. 2013). However, MnO nanoparticles and FeO nanoparticles were not only less toxic than their ionic counterparts but they also stimulated the growth of lettuce seedlings from 12% to 54%, respectively (Lü et al. 2016). Molybdenum nanoparticle also showed improved microbial activity and seed growth in chickpea after combined treatment with nitrogen fixation bacteria (Taran et al. 2014). In addition to germination, nanomaterials, such as ZnO, FeO, and ZnFeCu-oxide, are reported to increase crop growth and development with quality enhancement in many crop species including peanut, soybean, mung bean, wheat, onion, spinach, tomato, potato, and mustard (Dubey and Mailapalli 2016; Shalaby et al. 2016; Shojaei et al. 2019; Zulfiqar et al. 2019).

The basic economic benefits of the use of micronutrient nanofertilizers are reduced leaching and volatilization associated with the use of conventional fertilizers. Simultaneously, the well-known positive impact on yield and product quality has a tremendous potential to increase growers' profit margin through the utilization of this technology. Biosynthesized nanoparticles-based fertilizers and nanobiofertilizers should be explored further as a promising technology in order to improve yields while achieving sustainability.

26.6 Conclusion

The opportunity for application of nanotechnology in agriculture is prodigious. Research on the applications of nanotechnology in agriculture needs to be initiated in all sectors of agriculture. Nanotechnology promises a breakthrough in improving nutrient use efficiency through nanoformulation of fertilizers, breaking yield and nutritional quality barriers through bionanotechnology, surveillance and control of pests and diseases, understanding the mechanism of host–parasite interactions at the molecular scale, development of new-generation pesticides and safe carriers, preservation and packaging of food and food additives, strengthening of natural fiber, removal of contaminants from soil and water bodies, improving the shelf-life of vegetables and flowers, and use of clay minerals as receptacles for nanoresources involving nutrient ion receptors, precision water management, regenerating soil fertility, reclamation of salt-affected soils, checking acidification of irrigated lands, and stabilization of erosion-prone surfaces, to name a few. The use of nanomaterials for delivery of pesticides and fertilizers is expected to reduce the dosage and ensure controlled slow delivery. Nanotechnology has the potential to revolutionize the fertilizer use and has the ability to play an important role in crop nutrition. The usefulness and effectiveness of nanofertilizers to enhance the growth and yield has been clearly demonstrated. Nanomaterials could preferably be used for foliar application but can also be used as seed treatment or for soil application. Nanomaterials perform better under lower concentration and can enhance the nutrient use efficiency and improve soil fertility in an eco-friendly manner. However adverse impact of its use has also been reported. There is very limited knowledge about its long-term adverse effect on soil, plants, and ultimately on human. It is required to study about the non-toxic limit of nanoparticles related to its size and concentration. The positive benefit of nanoparticles should be selected on the basis of their risk related to environment and human.

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Introduction to Drone Technology for Natural Resource Management in Agriculture

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Abstract

Drones are transforming the face of global agriculture by providing enormous opportunities for precise management of agricultural inputs such as fertilizers, agrochemicals and natural resources such as soil and water. The impact of drone technology for agricultural management comes from its ability to survey a large area in short-time and providing real-time solutions by using modern data analytics tools. This chapter provides an introduction to drones, its components, types and softwares for drone deployment and image processing. It also includes an overview of drone application in different venues of agriculture and current research trends in the area of drone applications for natural resource management on a global scale.

Keywords

Agriculture · Sensors · Drone types · Drone application · Image processing · Natural resource management

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27.1 Introduction

Agriculture is facing many challenges due to climate change. The increasing frequency of abiotic and biotic stresses such as temperature, rainfall variability, extreme weather events, emergence of new pests and pathogens may reduce agricultural productivity. These changes have negative impacts on the agricultural production system and are a major threat to the food security of poor and marginized sections of society. The global population is expected to rise by 10 billion by 2050. However, the food resources on our planet will not be enough to meet this demand. To feed all these people, agricultural production needs to be increased. At the same time, the environmental impacts of agriculture needs to be reduced. For achieving this, sustainable use of soil and water resources has to be promoted, along with conservation of the forest cover and biodiversity (FAO 2019). One possible solution of this problem can be achieved by increasing the food production and minimizing the food waste.

Nevertheless, it poses a significant challenge to optimize agricultural management to achieve this goal. Prediction of diseases, yield forecasting, determination of the best harvest time and plant-growth monitoring are few ways to attain the goal of increasing food production by minimizing production cost in terms of fertilizer use, agrochemicals and irrigation requirement. At the same time, these are also some of the critical challenges that agriculture faces in order to become more efficient over time. Emerging, Unmanned Aerial Vehicle (UAV) or drone technology, remote sensing and computer vision have become essential tools to address these challenges. Certainly, drones can play a crucial role in addressing these problems. Drones are seen as one of the solutions to support next-generation agriculture (Sylvester, 2018).

27.2 What Are Drones?

The dictionary meaning of drone is the male honeybee. The single purpose of the male honeybee (drone) is to mate with the queen, followed by dying. A similar concept was used for unmanned remotely controlled pilotless aircraft for hitting the target, followed by self destruction during world war II military operations (van der Merwe et al. 2020). In recent decades, drones are not only used for military purpose, but it has expanded its horizon for civilian and commercial purposes including agriculture, parcel delivery, video filming and many more (Custers, 2016).

Some alternatives names of a drone are

1. Remotely piloted aircraft (RPA).
2. Unmanned aircraft system (UAS).

The drone is defined "**as remotely piloted aircraft controlled by a human pilot over a radio link or through autopilot technology feed through a software**" (Van der Merwe et al., 2020).

27.2.1 Types of Drone

Drones are primarily of four types—fixed-wing, single-rotor, multi-rotor and hybrid. Each drone type has its own advantages and disadvantages. The vertical take-off and landing (VTOL) for multi-rotor drones have only small operational requirements, whereas fixed-wing drones need a long and flat landing surface for smooth take-off and landing. Flight time or endurance is also affected by the type of drone used. Fixed-wing drones are most efficient, as the lift generated by the wings of the aircraft reduces the amount of energy needed to keep the drones airborne. The next most efficient drone types are hybrid systems, which may be single-rotor, multi-rotor to allow a VTOL capability and transition to fixed-wing flight to enable greater endurance (Vergouw et al. 2016).

27.2.2 Why Are Drones Used in Agriculture?

Drones are transforming agricultural as well as environmental applications. Drone images provide spatial information that helps farmers to make decisions on where and when to improve management practices in their field for crop mapping, monitoring and field analysis. With the help of a drone, a farmer can take a picture of his entire field to gather insights into the growth stage and health of his crop. Drones provide quicker, cheaper, comfortable and efficient surveys as compared to conventional surveys through eyes, tractor, satellites and aircrafts (Custers, 2016).

Let us understand how drones can help us to solve a challenging problem. Imagine a situation where a farmer is facing a problem with uneven growth of an arable crop. He found that the weed infestation is severely impacting his crop. Therefore, he needs information about the type and position of these weeds. To tackle these kinds of problems there is a need to understand the working chain of drone application (Fig. 27.1).

The drone application chain helps to identify the application of drone for its actual implementation for a specific problem. The starting point is the interest of the user

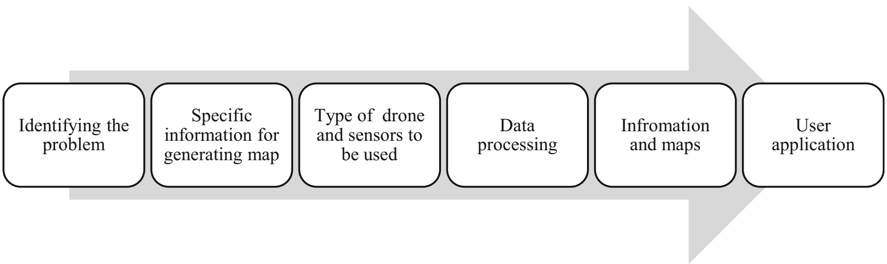

Fig. 27.1 Drone application chain (adapted from https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone)

for application of drones, e.g., a user may be interested in knowing about pest or disease infestation, crop health monitoring, soil moisture status of field, etc.

Depending upon the specific requirement of farmer, different kind of information is required for generating maps. It also determines the type of drones and sensors to be used for that particular purpose. Besides this, the different state and central laws and legislation for flying drones should also be taken into account. After getting the drone images, specific software is required for analysing the field condition in an efficient and automated way.

27.3 Drone as a Tool of Remote Sensing

Remote sensing is the science of getting information about the earth's surface without actually having any physical contact. Drones also acquire images like satellites, but the difference lies in the height of the sensor platform. Drone acquires images from few to 100 metres above the targeted areas, whereas satellites are revolving the earth over hundreds to thousands of kilometres. In case of drone remote sensing, the sun is acting as a light source. The sensor or camera attached with the drone is sensing, and recording reflectance from the target area. The drone imagery is processed, analysed and finally transformed into a map for interpretation (Liaghat & Balasundram, 2010).

The electromagnetic spectrum is the entire range of radiations measured by cameras or sensors. It consists of several wavelength regions, but only a few of them are useful for remote sensing. For example, visible region of the spectrum (400–700 nm) is utilized for detecting changes in plant health and related properties. The infrared region (700–2500 nm) plays a crucial role various in biotic and abiotic stress detection through remote sensing. The microwave region (1 cm–1 m) is used for remote sensing of moisture in soil and vegetation (Raj et al., 2020).

27.3.1 Spectral Signature

Drone imagery measures the amount of reflected light coming from the earth's surface. The spectral properties of the object determine the amount of reflected light in different parts of EM radiations. The amount of reflected light or reflectance is measured as a function of wavelength. The spectral curve produced is called spectral reflectance (Fig. 27.2). In the spectral reflectance curve, the reflectance ranging from 0 to 100% is shown on Y-axis, whereas the wavelengths of the electromagnetic spectrum are depicted on X-axis (Fig. 27.2).

In Fig. 27.2, water has low reflectance resulting in the dark colour of the water. Dry soil has a higher reflectance as compared to wet soil. The spectral reflectance curve of vegetation has a characteristic high reflectance in the near infrared region.

Before discussing the application of drones, readers should familiarize themselves with the concept of different types of resolutions used in remote sensing:

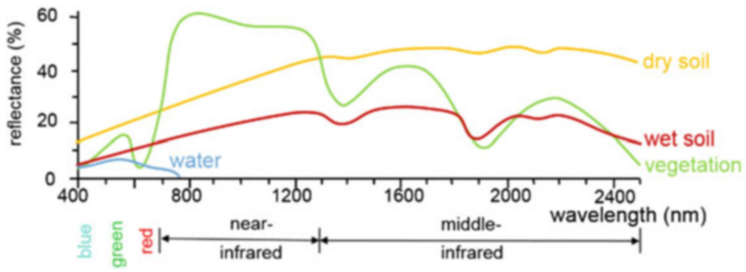

Fig. 27.2 Typical spectral reflectance curves for water, soil and vegetation. Image courtesy (https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone)

1. *Spatial resolution* refers to the smallest size of the object that can be differentiated in the image, and is commonly related to the pixel size of the image. Smaller the pixel size (or more number of pixels) better is spatial resolution and vice-versa (Lillesand et al., 2015).
2. *Spectral resolution* refers to the number of spectral bands used in the sensor. Higher number of the bands will give higher spectral resolution. Multispectral (more than 1 band) images store more information than panchromatic (having single band) images (Lillesand et al., 2015).
3. *Radiometric resolution* refers to the ability of sensor to distinguish very slight differences in the energy captured by the sensors. It is the sensitivity to the magnitude of electromagnetic energy which determines radiometric resolution. For e.g., Hyperspectral sensors have higher resolution as compared to multispectral or panchromatic sensors or camera (Lillesand et al., 2015).
4. *Temporal resolution* refers to the frequency with which images are collected over the target area over a while. It helps to detect changes over a period of time (Lillesand et al., 2015).

27.4 Drone Components: An Introduction

Drones have become very popular over the past five years. Furthermore, the number of drones being sold is still increasing. The most important reason for this development is improved technologies, e.g. better batteries, electrical motors and also smaller electronics and of course everything at a lower cost. A large variety of drones has been developed over the past few years varying in size, weight, number of motors, colour and design. Still, some basic concepts are same for all drones.

27.4.1 Main Components of a Drone

See Fig. 27.3.

Fig. 27.3 Main components of a drone system: Drone, remote control, a ground control station (tablet) and drone battery. Image courtesy (https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone)

27.4.2 Drone Platform, Remote Control and Ground Control Station

The drone itself is the platform for drone movement, and a remote control is used to control its movement. In many cases, a laptop or tablet is connected to the drone. This computer or laptop is used as a ground station, having software that provides all kinds of information, such as the battery status, drone movement, a map with an overview of flight area and real-time images from the drone camera. The ground station also translates the signal from the remote control into the speed of the motors (Juniper 2018).

27.4.2.1 Batteries

Batteries are important components of drones. It provides the electrical power to move the motors. A larger battery size means more capacity and higher time for flight. The main types of batteries used for drones are lithium polymer (LiPo). These types of batteries should be used cautiously. It should not be over-charged; over-heating may result in short-circuit, which sometimes leads to fire and other catastrophic events (Juniper 2018).

27.4.2.2 GPS

It is used to determine the location of the drone. The GPS data is used to create a flight log, storing the coordinates of the flight. Besides, this location data is used for real-time tracking of the drone on the map shown on the ground control station (Juniper 2018).

27.4.3 Sensors and Cameras for Drones

Sensors are typically used for point measurements of particles in air or water. These chemical sensors have the sensitivity to measure the concentration of a selection of substances. These sensors can be used to measure the greenhouse house gases or particulate matter concentration in the microclimate of trees or orchards. It may also be used to measure ethylene concentration, which is an indicator of fruit ripening or it can also be used to monitor irrigation water quality in the channels, ponds or lakes. The camera in the drone is one of the important components used for monitoring soil and plant conditions in different situations. Cameras are becoming smaller and lighter to fit the drone (Krishna, 2018). The main types of cameras and their application are given below:

27.5 Types of Drone Based on Rotors/Wings

Two main types of drones can be distinguished: multi-rotor drones and fixed-wing drones. Fixed-wing drones look like an aeroplane and can be identified by their rigid wing. Because of this rigid wing, they cannot do vertical lifts. Instead, they glide to higher altitudes. Multi-rotor based drones look more like a helicopter but have multiple rotors. Control of drone movement, in this case, is achieved by varying the relative speed of each rotor. Multi-rotor drones are constructed with varying number of rotors. Common types are tricopter, quadcopter, hexacopter and octocopter referring to systems with 3, 4, 6 and 8 rotors. In case of four rotors, it is called a quadcopter, and with eight rotors an octocopter (Vergouw et al., 2016) (Fig. 27.4).

Fig. 27.4 Examples of multi-rotor (left) and fixed-wing drone (right)

27.5.1 Flying a Drone

To start flying a drone, user needs at least two parts: the drone itself and a remote control, which is connected with the drone. With the two sticks of the remote control, you control the movement of the drone. One stick to bring the drone up and down and rotate the drone, and the other stick to move the drone in different directions.

27.5.2 Choosing the Right Camera or Sensors

The attached camera or sensor with drones will be vital for application for different purposes. A range of lightweight cameras is available for drone-based acquisition. There are three important types—(a) RGB: the RGB camera makes images in the visible region, often with great spatial detail. (b) Multispectral: the multispectral camera acquires images in several spectral bands (Table 27.1). This camera captures five images at the same time and provides data with more spectral detail. (c)Thermal: the thermal camera detects the temperature differences. It can be used to detect stress in plants. A higher temperature means more stress, comparable to when you do not feel well and have a fever. In addition to cameras, different kinds of sensors can also be attached to a drone. For example, to measure water quality by sampling small quantities of water or to measure particles and gases in the air (Tokekar et al., 2016) (Table 27.2).

Table 27.1 Different types of cameras and their application for agricultural management

Camera type	Main characteristics	Applications
RGB	Red, Green, Blue light Great spatial detail Resembles visual observations	Crop monitoring Weed detection Plant cover
Multispectral	More spectral bands Information in near-infrared Higher costs	Plant health Biomass and yield mapping Nutrient deficiencies
Thermal	Measures temperature differences More complex measurement Higher costs	Irrigation and water management Soil water status Disease mapping
Hyperspectral	Measure minute differences in energy over several bands Information in hyperspectral bands (250–2500 nm) Higher costs	Nutrient stress Drought monitoring Disease detection
LIDAR	Measures 3D information in a detailed way Complex measurements Higher costs	3D mapping of soil Estimation of tree and plant height Determination of canopy architecture

Adapted from Bogue (2017)

Table 27.2 Comparison between multi-rotor and fixed-wing drones

	Multi-rotor drones	Fixed-wing drones
Benefit	Manoeuvrability Compact design Increased payload capacity Ease of use	Increased flight range Stability in windy conditions Ability to recover from power
Drawback	Limited flight range	Take-off and landing area required More difficult to fly Less manoeuvrable Larger dimensions Increased cost

27.5.3 Applications of Drone Technology

Some applications of the use of drones are mentioned below:

1. Farming communities are hit hardest by the wrath of climate change. Therefore, agriculture needs to adapt to climate change by using innovation in technologies to enhance decision making through real-time to tackle these problems and generating climate-proof sustainable solutions (FAO, 2019). Drones emerged as a tool for supporting real-time monitoring of small farms for assessing in-field spatial variability and evidence-based planning that can provide valuable data that can influence farmers' decisions and can also be used by policymakers for making robust decisions for future farming (https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone**)**.
2. *Crop production*—Precision farming is based on the principle of assessing in-field variability of soil and nutrients by using sensors and imaging with real-time data to enhance farm productivity. Drones can support precision farming by sensing soil health, assist in fertilizer application, estimate yield data and provide valuable data for weather analysis (Rani et al., 2019). Many studies have shown the successful use of drones such as DJI Agras MG-1 for variable rate application of agrochemicals such as herbicide, insecticide and liquid fertilizers. It can also be used for generating multispectral and hyperspectral imagery in creating Normalized Difference Vegetation Index (NDVI) maps, which can differentiate soil from plants, detect plant stress and can also detect crop types (Huang et al. 2014).
3. *Crop insurance*—Drones can also be used for estimating crop losses due to abiotic stresses and claim settlement with transparency. In India, drones are used by various companies such as Skymet to provide services to insurance companies to settle claims of crop losses in the state of Gujrat, Maharashtra, Madhya Pradesh and Rajasthan (Van der Merwe et al., 2020).
4. *Monitoring Disaster risks*—Drones are used for monitoring landslides and soil erosion, that can be used for disaster preparedness to inform agricultural communities to reduce their impact (FAO, 2019).

5. *Wildlife conservation*—Drones with thermal cameras are used to track and monitor wildlife and livestock. It can also be used to inspect poaching activities by identifying them through their thermal signatures, even if poachers are hidden in thick forest (Sylvester, 2018).
6. *Soil and field variability assessment*—Drones can be used for aerial imagery to produce precise 3D maps for soil. They can be used for planning planting of crops and nutrient application (Raj et al., 2020).
7. *Planting*—Drones can be used for shooting seeds encapsulated with nutrients in the soil with an average uptake of 75 percent, thus bringing down costs for planting in a forest and hilly regions for the conservation of natural resources (Rani et al. 2019).
8. *Crop spraying*—Drones can use variable rate application of agrochemicals such as pesticides and herbicide in the soil, ensuring homogenous coverage for controlling weeds and insects (Raj et al., 2020).
9. *Crop monitoring*—Drone imagery helps to generate animations for crop growth and identifying stresses at different stages and influences of different treatments in experimental design on crop health for getting better insights in research and also enables better crop management (Krishna, 2018).
10. *Irrigation*—Drones with hyperspectral, multispectral or thermal sensors can identify which parts of a field are moisture deficient or need improvements (Krishna, 2018).
11. *Health assessment of soil and vegetation*—Drones with sensors of infrared, multispectral and hyperspectral can analyse soil and plant health precisely and accurately. NDVI data, in combination with other indexes such as the Crop-Water Stress Index (CWSI), Canopy-Chlorophyll Index (CCCI) in agricultural mapping, helps to analyse the current situation of plant stresses. The general principle of NDVI is to detect changes in reflectance of infrared light from a healthy plant to a stressed plant. When a plant becomes stressed through the loss of moisture or by infestation with disease or pathogen attack, it reflects less near infrared light (NIR), which can be used as a signal for detecting stressed plants from healthy ones (Sylvester, 2018).
12. *Crop acreage estimation*—Drones can be easily used to estimate the precise crop area and crop stage of a farm. Thus, harvesting time and yield estimation can be done quickly by using drone imagery (Sylvester, 2018).
13. *Locust warning*—Drones can be successfully used for monitoring locust flight paths across the country for warning farmers to manage their crops for the forthcoming attack of locust in the advancing regions (Sylvester, 2018).
14. *Cattle herd monitoring*—Drones can be successfully employed in tracking the movement of cattle herd; it is especially useful at night using thermal cameras due to the inability of human eyes to see under dark conditions (Sylvester, 2018).
15. *Monitoring illegal fisheries activities*—Drones can be employed in coastal areas to track the movement of ships and detect illegal fishing activities (Sylvester, 2018).

16. *Monitoring malfunctioning of irrigation equipment*—Drones can detect the malfunctioning of equipment present in the field. It can detect the nozzle and sprayer damage-causing heterogeneous moisture conditions in the field, which is difficult to detect manually (Krishna, 2018).
17. *Observation of atmospheric stresses*—Drones can be used for observing atmospheric stresses such as cyclone, tornado, ozone concentration in atmospheric. It can also detect changes in the microclimate of the field by detecting changes in atmospheric humidity, CO2 concentration. U.S. Meteorological stations are using drones for gathering weather data and atmospheric processes since 1946 (Krishna, 2018).
18. *Yield estimation*: Conventionally, yield estimation in orchards is a very tedious, time-consuming and labour-intensive process if it is done manually. However, cutting-edge drone technology helps us to provide images on which scientists can develop a machine vision algorithm to automate this process. Helps farmers to plan for harvesting time as well as improving their marketing channels for getting better profitability on their produce (Krishna, 2018).
19. *Drone for real-time monitoring of wildfire*: There are emergencies like fire when real-time information assists in controlling fire to firefighters and rescue people trapped inside it. It also provides the composition of air to understand its environmental impact (James et al., 2019).
20. *Scientific research*: Drones can be mounted to various types of sensors for detecting GHG concentration in the field under different kinds of management practices. For example, drone can be used to observe the changes in carbon dioxide, nitrous oxide and methane concentration in the air after application of fertilizers or manures or by mixing green manure over a period of time. This data is generated in real-time and helps farmers to manage the field quickly. Drone helps to measure the concentration of harmful gases, which can be used to monitor environmental quality and provide caution to the people about the health hazard and to manage the situation (https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone).
21. *Pest and disease detection in the fields*: RGB camera is used to locate weed infestation and the type of weeds present in the field and to develop a map for precise application of herbicide to control weeds without applying any herbicide where it is not required. By applying herbicide by drones, less herbicide is used, and the environment is also protected. Drones produce a large number of images in which both weeds and crop are present. Therefore, machine learning algorithms are used to train computers to classify weeds from the crop. For this, several images of weeds are used to train the neural network used in machine learning to classify the weeds from the crop. It will help to automate the process of weed identification in the field and getting a precise location for the application of herbicide. Drones can be successfully employed to monitor disease and pest incidence by using multispectral images and thus, calculating plant stress index. The plant showing higher stress index is considered to be infected with disease or pest, and it can also be used to calculate yield loss due to these disease and pest attack (Huang et al. 2014; Krishna, 2018).

22. *Real-time flood monitoring*: Drones can generate maps with areas of submergence after flooding events in real-time so that farmers can decide to drain their fields as quickly as possible. Besides, farmers can also determine the yield loss due to the flooding (Suroso 2019).

27.6 Advantages of Drone Application

Satellite imagery is the only source for crop monitoring from space before the dawn of drone technology. Satellite systems of Sentinel-2 and LANDSAT are regularly used for monitoring crops. These satellites have global coverage and fixed spatial and temporal resolution. They lack various spatial details that are required by a farmer on this field for better managing his farm. On the other hand, Drones provide a flexible alternative to decide the time of drone flight, sensors and cameras mounted on it depending upon the information needed by the user/farmer (Table 27.3).

Limitations of drones over satellite systems

1. *Coverage*: Limited to only a portion of the field, but satellite has global coverage.
2. *Flight time*: Drones can fly only for few hours depending upon the capacity of the battery used inside it, but satellites are revolving around the earth regularly.
3. *Cost of the drone system*: The drone system is very costly, whereas satellite imagery is usually free to download and to be used.

Therefore, using a drone is not always the best solution. Generally, scientists combine the drone and remote sensing for agricultural applications. Satellite imagery is used to monitor crop growth at the field level. In contrast, drone produces detailed maps to identify the limiting factors such as pest and disease, soil moisture levels and plant health within the fields.

Table 27.3 Advantage of Drones over satellites

Parameter	Drone	Satellite
Timing of drone flight	Variable	Fixed
Number of observation	Variable	Fixed
Type of camera or sensor	Variable	Fixed
Provide real-time overview	Yes	No
Can be operated in unfavourable cloudy condition	Yes	No
Can be used to present 3D images from acquiring several images from the field over a period of time	Yes	No

27.7 Safety and Legislation While Flying the Drone

In aviation terminology, drones are called remotely piloted aerial system. There are specific rules and regulation in each country for safe drone flying and maintain the privacy of their citizens. There are a few standard rules applied to every drone pilot. Drones are allowed to fly up to a set height.

1. While flying a drone, it must be visible to the pilot.
2. Do not fly it over a group of people or to private property, roads or to train tracks.
3. Do not fly near the airport as this may cause serious consequences.

27.8 Rules and Regulation for Flying Drones in India

The Directorate General of Civil Aviation launched a drone policy in December 2018. It allows the use of drones for agricultural purposes for imaging and Aerial survey but restricted its use for chemical and pesticide spraying. The standard working protocol for drone use in India is governed by Unmanned Aircraft System (UAS) rules—Part-VI published by the Government of India (https://digitalsky.dgca.gov.in). The general laws of using drones are as follows:

1. Drones should be registered for flying in India.
2. Foreigners are not allowed to fly drones without prior permission, and they must take a unique identification number from government authorities.
3. Drone pilot must have maintained a direct visual line of sight while flying Drone.
4. Drones cannot be flown more than 400 feet vertically.

Before every single flight, it is required to request permission to fly drones via a mobile app, which will automatically process the request and grant or reject it. India is calling this system "No Permission, No Take-off" (NPNT). If a drone pilot tries to fly without receiving permission from the Digital Sky Platform, he or she will simply not be able to take off ((https://digitalsky.dgca.gov.in). All the information regarding rules, regulations and permission are available on the DGCA website.

27.9 Preparation of Drone Flight

1. Check the status of Drone: All the equipment should be checked thoroughly to ensure their proper functioning. The batteries should be charged, sensors or cameras should be appropriately mounted to ensure a safe flight. Besides this, weather conditions should also be checked to reduce the chances of last-minute cancellation of drone flight. Every country has its own rules and regulations for flying drones in a particular area, which must be followed sincerely.
2. Safety check: It is essential to do a field assessment of the take-off and landing site. It must be assured that there is a safe distance between the flying areas and

roads, animals, people and buildings enough. The local rules and regulations must be checked before flying drones over an area.

3. Laying outfield with ground control point: Ground control point helps to know the precise location of the field. Circular placards that are laid at the corners of the field and one placard is placed at the centre. Their precise coordinates are determined by GPS RTK (Real-Time Kinetics). If the drone has embedded RTK, then laying of ground control points is not required.

27.10 Image Processing

Drones produce a large number of aerial images. These images are stitched together depending upon their image identification number and acquisition time from metadata of the camera.

27.10.1 Orthomosaicking

Drones generate a large number of images. When these images are correctly connected, then orthomosaic is produced. These orthomosaic provides an accurate two-dimensional georeferenced image of the field, and it can be utilized for various purposes such as moisture stress, weed and pest infestation, soil fertility maps, crop health status and estimation of yield. UAV images can be used to create 3D images from a series of 2D images by using a technique structure-from-motion (SfM). The most desirable products are digital elevation models and point clouds (Mohan et al. 2017).

27.10.2 Image Survey Parameters and Requisite

Survey parameters depend upon the purpose of imaging. If a farmer wants to detect small patches of pest infestation, then the higher spatial resolution of an image is required. Let us understand spatial resolution.

1. Spatial resolution: It depends upon the number of pixels per image or number of pixels used to construct an image. The higher the number of pixels, better is the spatial resolution of the image (Lillesand et al. 2015). For example, an image with 1 mm per pixel denotes higher resolution as compared to 10 cm per pixel (Fig. 27.5). Generally, mm and cm are used in drones for image acquisition, whereas metres and kilometres are used in satellite imagery.
2. Overlapping—It is very important in orthomosaic generation from drone images in order to ensure that at least three points can be matched in a set of adjacent images and to avoid tilting or variance during the flight. As a rule of thumb, the front (along the track) side overlappings (across the track) should not be less than 60% and 20%, respectively (Fig. 27.6) (https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone).

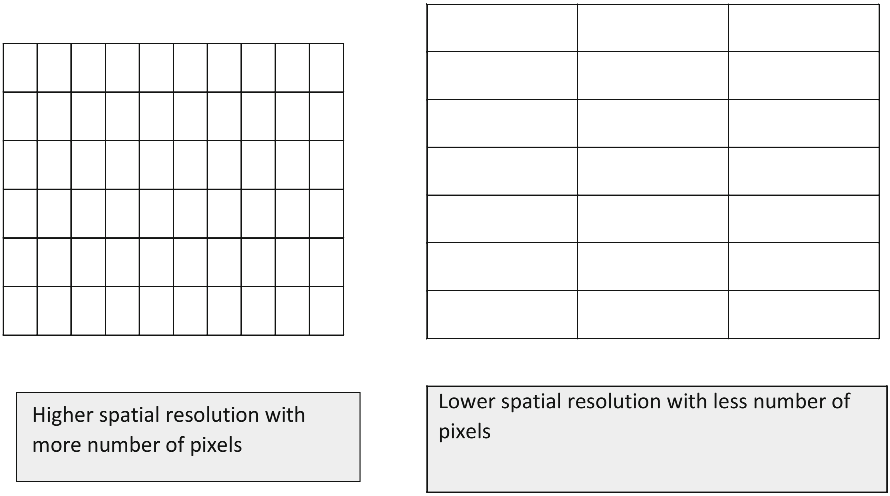

Fig. 27.5 Comparison between pixel sizes of the image

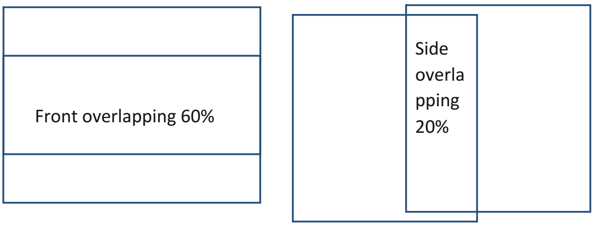

Fig. 27.6 Front and side overlapping requirement for orthomosaic generation

3. Flying speed: If the drone is flying very fast, it will produce blurry images, and if too slow, it cannot complete its task in a single fight. So, there are always trade-offs between speed and image quality. Therefore, a steady optimum speed is always maintained to capture the whole area with good image quality (https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone).

27.11 Computation of Waypoint for Aerial Surveying

Waypoint is landmark positions on the ground having a precise GPS location which can be used for generating GPS position for the entire field. The geographic coordinates are composed of longitude, latitude and altitude. Nowadays, waypoints are automatically calculated by the GPS receiver of the drone. The number of waypoints required to survey is a field equal to the size of the field divided by the field-of-view provided by the UAV camera (Fig. 27.7).

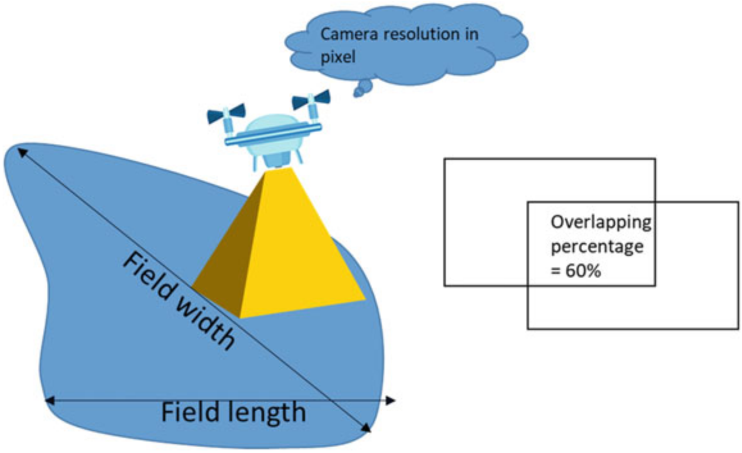

Fig. 27.7 Graphical presentation for requirements of waypoint calculations

27.11.1 How Many Waypoints Do you Need to Get Pictures from All My Fields?

The number of waypoints that are necessary to survey a field thoroughly is computed by dividing the size of the field, by the field-of-view provided by the UAV camera. We need to define the spatial resolution of the camera for the orthomosaic generation. To know about the area covered by UAV, we need three parameters, viz. field width, field length and resolution of the camera in pixel. The overlapping percentage is also required for the orthomosaic generation.

If we divide camera image resolution by the number of pixels in 1 m, we determine how much area will be covered. This can be presented in the form of a simple formula.

$$\text{No.of waypoints in x} - \text{axis} = \frac{\text{length}}{\text{Dx}} \tag{27.1}$$

$$\text{No.of waypoints in y} - \text{axis} = \frac{\text{length}}{\text{Dy}} \tag{27.2}$$

Here, Dx and Dy are the area covered by a camera on the ground. The coordinates of waypoints can be determined by generating a regular grid where the distance between the coordinates points is defined by the sizes from the area covered by the UAV camera on the ground. Overlapping parameters are also used to shrink the coordinates by the defined percentage of overlapping. The flying height can be computed with the camera focal length, sensor size and image projection on the ground by this simple formula (3).

$$\frac{h}{f} \equiv \frac{d}{d_s} \tag{27.3}$$

where h = height of drone; f = focal length of camera; d = area covered by camera on the ground; ds = size of camera sensor. The specifications of the camera can be easily found in specifications booklet of the camera provided by the manufacturing company (https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone).

27.12 Need of Ground Control Application

Flying drones is an enjoyable activity but it does not gives good precision in imagery for surveying. Therefore, we need ground control stations which provide us even and consistent images of good quality without loss of any information. A ground control station is a software application that communicates **your UAV using wireless datalinks.** It allows to read live data from the drone, send commands and control UAV. Ground control stations will allow us to plan and setup autonomous survey missions. A ground control station will also allow us to monitor the state of our UAV during flight, oversee the progress of the mission and configure various parameters of our drone (https://www.edx.org/course/drones-for-agriculture-prepare-and-design-your-drone).

There are various softwares available on internet which can be used as a ground control station for drone flight missions.

1. QGroundControl—It is a multi-platform open source ground control station software that allows users to fully control and plan a mission for any MAVLink enabled drone (http://qgroundcontrol.com/).
2. MAVLink (Micro Air Vehicle Link)—It is a messaging protocol for communicating with small UAVs. This protocol was released under an open source license and is very lightweight, efficient and one of the most popular communication protocols for ground control stations and UAVs (https://mavlink.io/en/).

After flying the drones using a ground control station we need to produce orthomosaic maps which is a stitched image of various images taken from the camera during the flight of UAV. Before going into image processing, we need to understand some basic concepts related to UAV orthomosaic images.

1. **Geometric correction**—It includes the corrections of errors related to lens distortion, camera tilt and relief (terrain) effects, to obtain an accurate undistorted representation of the area, just like a map. Geometric correction orthomosaics allow us to measure true distances directly from the image as the scale of the image is uniform (van der Merwe et al. 2020).
2. **Storage format of georeferenced orthomosaic images**—One of the most common file formats for storing georeferenced data is *TIFF*. TIFF (or TIF), which

stands for Tagged Image File Format, is a file format used for storing images along the information about map projections, coordinate systems, ellipsoids and everything else necessary for the spatial location of the file (Khan and Miklavcic 2019).

Geographic coordinate systems and projections - Atitude, longitude and altitude coordinates, called geodetic coordinates. The most common systems used for standard geographic coordinates is the World Geodetic System (WGS 84) which is the same standard used for the nowadays ever-present Global Positioning System (GPS). WGS uses latitude and longitude coordinates based on a reference ellipsoid that best approximates the shape of the earth. To translate longitude and latitude coordinates to a map we use map projections. The most common systems used for standard geographic coordinates is the World Geodetic System (WGS 84), alos used in Global Positioning System (GPS). The UTM projection divides the world in 60 different zones and it projects each of those zones into a plane. Unlike WGS84, UTM's coordinates are given in meters and with respect to the left inferior corner of the zone. This coordinate is given along the x (Easting) and y (Northing) axisrise Mercator or UTM, but there are many other projection types(Panigrahi and Panigrahi, 2018).

27.13 Image Processing Softwares for Drone Orthomosaic

1. *Open Drone Map* is used for the creation of orthomosaics (ODM). ODM is an open source project that will allow you to generate and visualize maps, point clouds, 3D models and digital elevation models from your aerial images (https://www.opendronemap.org/).
2. *QGIS* can be used after the creation of the orthomosaic. QGIS is a free and open source Geographic Information System for processing. With QGIS users will be able to visualize and transform their data to gain information from it (https://qgis.org/en/site/).
3. *webODM*—Apart from the Command Line Interface, ODM Also Has a Version with a More User-Friendly Interface: WebODM. This Makes it Much Easier for Beginners to Process their Datasets (whttp://webodm.wur.nl/ur.nl)
4. *Pix4D*—Pix4D is a software used to convert multispectral images into accurate reflectance and index maps, such as NDVI and RBG images (https://www.pix4d.com/).

27.14 Information Obtained from Orthomosaic After Image Processing

1. Image processing software provides measurements like length, area and volume from your orthomosaic or point cloud. For example, it can be used to obtain DEM (Digital Elevation Model) to monitor the height of crops during the season.

2. *Vegetation indices*—Several vegetation indices can used to obtain hidden information about the crop health conditions such as plant phenotype, stress levels, productivity, growing season length, moisture and nutrient stresses.

27.14.1 The Most Commonly Used Vegetation Indices Are Mentioned Below

1. Normalized Difference Vegetation Index (NDVI).

$$\mathrm{NDVI} = \frac{NIR - R}{NIR - R} \tag{27.4}$$

NIR near-infrared band, *RED* red band

NDVI is a kind of structural index. It is used to monitor different aspects of the field such as canopy coverage and density, frost damage detection, early disease detection, biomass production and soil moisture levels (Jackson et al. 1980).

2. Normalized Green Red Difference Index (NGRDI).

$$\mathrm{NGRDI} = \frac{\mathrm{G} - \mathrm{R}}{G + R} \tag{27.5}$$

G green band, *R* red band

NGRDI can be used to detect differences in green canopy areas and it is used as an indicator of chlorophyll content in various crops like soybeans, alfalfa or corn. It can also be used for biomass and crop yield estimation (Hunt et al., 2005).

3. Green Leaf Index (GLI).

$$\mathrm{GLI} = (2 \cdot \mathrm{G} - \mathrm{R} - \mathrm{B})/(2 \cdot \mathrm{G} + \mathrm{R} + \mathrm{B}) \tag{27.6}$$

G green band, *R* red band, *B* blue band.

Green Leaf Index can be used to differentiate between soil and vegetation, and can be used as an indicator of chlorophyll levels (Hunt Jr et al. 2013).

4. Visible atmospherically resistant index (VARI).

$$(\mathrm{G} - \mathrm{R})/\mathrm{G} + \mathrm{R} - \mathrm{B}) \tag{27.7}$$

The VARI index is used to accentuate vegetation areas using visible images. It does so while reducing the effect of illumination differences and also atmospheric effects (Gitelson et al. 2002).

5. Triangular Greenness Index (TGI).

Adjusted to the typical wavelengths of CMOS sensors, its formula is:

$$\mathrm{TGI} = \mathrm{G} - 0.39 \cdot \mathrm{R} - 0.61 \cdot \mathrm{B} \tag{27.8}$$

TGI is one of the best Vegetation Indices for leaf chlorophyll measurements, and can be used to indirectly measure plant nitrogen content. It has the benefit of only using visible spectrum photographs and being relatively insensitive to leaf size (Hunt Jr et al. 2011).

6. Normalized Difference water Index (NDWI).

$$\mathrm{NDWI} = (\mathrm{R860} - \mathrm{R1240})/(\mathrm{R860} + \mathrm{R1240}) \tag{27.9}$$

R860 Red band at 860 nm wavelength, *R1240* Red band at 1240 nm wavelength.

NDWI index helps to determine water status of leaf. It is an indirect method for determining plant water stress under drought conditions (Stimson et al., 2005).

27.15 Current Studies Related to Use of Drones in Natural Resource Management Studies: Drones Application in Conservation Agriculture and No-tillage

Drones have potential to boost the no-tilled and conservation agriculture system due to its precise and real-time detection capacity of farm surveillance. Drones imagery can easily spot weed infestation which is a crucial problem in no-tilled and conservation agricultural systems. Drones can perform several operations like spot-spraying on weeds and pathogens, spraying liquid fertilizers on nutrient stressed plants. Thus, helping a lot to farmers in reducing cost of cultivation and planning management practices in the fields (Krishna, 2018).

Tripicchio et al., 2015 used a novel approach for differentiating soil tillage condition, i.e. tilled and no-tilled soils by using RGB-D sensors mounted on drones during its flight. This can be achieved by developing computer-vision based approach to generating two different algorithms to classify soil surface roughness characteristics. Actually, satellite imagery cannot be utilized for detecting changes in surface roughness characteristics due to ploughing methods. So, the present method provides an approach to develop correlation between radar remote sensing acquired parameters and soil roughness values obtained from RGB-D cameras or laser scanners.

27.15.1 Drones for Precision Management of Soil Fertility and Crop Productivity

Drones known as "eye in the sky" will be powerful instrument for managing agricultural activities in the future. It may act as key component in survey, surveillance and soil fertility management. Drones have a great ability in capturing detailed imagery of soil and crop which can be processed through inbuilt software. It helps farmers in precise management of crop and soil fertility. Globally drones are used for deciding management practices instantaneously and accurately with less human labour and cost involved (Tigue 2014).

Unlike manual photography, drones have extraordinary advantage to take images from low altitude and vantage locations over the crop canopy (Krishna, 2018). Drones have revolutionized the way of collecting information about variability in soil fertility and its impact on crop growth. Drone mounted with advanced sensors can easily analyse soil fertility status quickly which was not possible few years back. Variable rate applicator uses the soil fertility map for applying precise amount of fertilizer in the field (Taylor 2014).

The real power of drones comes from the advanced sensors which can help to show the degree of soil weathering, texture, colour, tillage intensity, clod size, erosion intensity and topography of land. Soil maps produced by using thermal cameras can be used to generate surface moisture condition of field (Table 27.4).

27.15.2 Scope of Drone Technology in Indian Agriculture

Although Indian agriculture is facing many challenges of crop production under adverse climatic situation, it has lot of potential to improve and make the farming profitable in a sustainable way. The Indian government has taken many initiatives for transforming agriculture through innovation and technology. The state government of Maharastra has announced to work with drone companies to survey drought affected areas with drones to improve irrigation facilities and crop yield (https://www.futurefarming.com/Machinery/Articles/2019/4/Indian-state-turns-to-drones-to-modernise-agriculture-413234E).

Many universities and research organization working together to reduce the cost of drones and making it more compatible for agricultural purposes under Indian situation. Many start-up companies are working in drone manufacturing and providing services to farmers by surveying their fields by using drone technology and providing them instant solutions and advise for problems arising in their field. The future of farming will be soon transformed and drones flying over fields will be a common view in near future.

Table 27.4 Application of drones in different studies related to agriculture and natural resource management

Sl. No	Site	Drone specifications	Objective	Sensors	Findings	Reference
1.	Belgium	X8 model having eight motors and four arms, payload capacity—7 kg Consisting of GlobalSat BU-353S4 lightweight GPS, microcomputer for controlling application and smartphone for remote control	1. To test the efficacy of GPR for soil moisture mapping 2. To present a new airborne frequency-domain GPR made of vector network analyzer and horn-dipole antenna	Ground penetrating radar (GPR)	Drone mounted GPR can be employed for fast, accurate, high resolution mapping of soil moisture at field scale to support precision agriculture and environmental monitoring	Wu et al. (2019)
2.	Armenia	DJI phantom 3 drone	1. To study the possibility of use of drones for agricultural management practices such as accurate measurement of field, 3D mapping, supervise crops and visual inspection of crop health	12.4 MP camera	3D maps generated in the study provide an opportunity to update cadastral maps which can be utilized for future crop production in Armenian agriculture	Hovhannisyan et al. (2018)
3.	Brazil	SX2 fixed-wing drone	To determine management zones through image processing for precision agriculture	RBG camera	Management zones identified with the help of drones can help farmers to apply precisely fertilizers, herbicide and irrigation to maximize profit and minimizing agricultural cost per hectare	Silva et al. (2017)
4.	San Bartolo, Italy	Multirotor hexacopter ESAFLY A2500_WH	To extract vegetation indices (VI) such as t normalized difference	RBG camera	Multispectral images obtained through aerial survey by drones can be	Candiago et al. (2015)

			vegetation index (NDVI), green normalized difference vegetation index (GNDVI) and the soil adjusted vegetation index (SAVI) for examining crop health and its stresses		utilized for fast and reliable technology for crop health assessment	
5.	Italy		To generate 3D point cloud maps of vineyards for managing path and operations using drones	Multispectral camera	The innovative unsupervised algorithm for vineyards detection was found to be efficient and robust: Reliable results were obtained even in the presence of dense inter-row grassing, many missing plants and steep terrain slopes.	Comba et al. (2018)
6.	USA		To survey the land and generate high resolution 3D images		To decide management block formation, deciding type of crop and its variety and laying irrigation channels in the field	de Landgrafit (2014)
7.	USA	Robota LLC, TX, USA	Mapping of soil topography and locating ground sampling spots	Multispectral camera with 5 bands—R, B, G, red edge, NIR	2D and 3D topography, soil mapping and locating ground sampling spots	Robota LLC (2015)
8.	Germany	SUSI 62/geo technics	Mapping of field topography, soil types, soil moisture and temperature regimes Formation of management blocks	Nikon 300 D; canon D5 mark II	2D and 3D mapping of field; detection of soil types; determination of soil moisture and temperature regimes; formation of management blocks	Thamm (2011)

(continued)

Table 27.4 (continued)

Sl. No	Site	Drone specifications	Objective	Sensors	Findings	Reference
9.	Switzerland	eBee/Sensefly Inc., Switzerland	For field surveying of crop, weeds and pest detection, soil moisture and temperature mapping	Multispectral cameras for multispectral images; Thermo map for moisture and temperature	To generate soil surface maps of moisture and temperature	SenseFly Inc (2016)
10.	Germany	AscTec humming bird; neo AscTec GMBH, Germany	Mapping of soil erosion	Sony alpha 7R- 36MP	Mapping of agricultural fields for monitoring of soil erosion	AscTec (2016)
11.	Spain	Md4–200/microdrone GMBH, Germany	To compare an index related with sunflower N-status, to study the effect of applied nitrogenous fertilizer on NDVI, LAI, leaf-N and canopy growth	ADC lite tetracam, 590–920 nm band width	UAV-based estimate of NDVI is better than ground-based system for N-applied through fertilizer on crop growth	Agüera et al. (2011)
12.	USA	Lancaster/precision hawk, Inc., IN, USA		Multispectral cameras	Aerial mapping of agricultural fields, determination of plant density and soil moisture Detection of gaps within rows NDVI calculation, chlorophyll and N-status of plant	Precision Hawk LLC (2016)
13	Canada	Aeyron, scout/Aeyron Inc., Ontario, Canada		Multispectral cameras	Crop scouting, detecting response of organic manures and inorganic fertilizers on crop growth	Zhang et al. (2014)

14	USA	AgEagle Aerial Systems, Kansas, USA		Multispectral cameras	Mapping of agricultural fields for crop growth and soil nutrient status, preparation of maps for recommending fertilizers and pesticide	AgEagle Aerial Systems Inc (2016)
15	Germany	AscTec GMBH, Krailling, Germany		Panasonic Lumix DMC LX 3	Mapping of soil erosion, rill and gully formation	Eltner et al. (2013)

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High-Throughput Estimation of Soil Nutrient and Residue Cover: A Step Towards Precision Agriculture

28

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Abstract

Soil nutrient measurement is an integral part of farming. Several protocols exist for soil sampling and measurement of soil nutrients such as N, P, K, organic matter, soil moisture, and residue cover. However, the measurement methods are labor intensive and have lower spatial and temporal frequency. Several proximal sensing methods have been developed for faster measurement, but they are slow due to redundancy. Therefore, newer methods are being developed which exploit the optical properties of soil. Optical properties of soil affect the reflectance of radiations from the electromagnetic spectrum. This spectral reflectance can be quantified and the variation among them can be used to distinguish between soil constituents. Technics to detect and quantify the soil spectral reflectance is known as remote sensing. In this chapter we would discuss the technological advancements related to remote sensing such as aerial sensors, faster data collection, automated analysis using statistical and machine learning tools, and to use the data to train models for nutrient and residue cover estimation. This data can be used to develop soil nutrient deficiency map for variable rate management of resources. Therefore, a systematic appraisal and critical investigation of various remote sensing tools to estimate soil nutrient content and residue cover will improve our understanding of the subject and pave the way for further research in this direction.

Keywords

High-throughput (HT) · Proximal sensing · Remote sensing · Soil nutrients · Residue cover · Precision agriculture

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28.1 Introduction

High-throughput (HT) techniques for agriculture include the use of advanced technologies for fast and accurate collection, extraction, and analysis of plant or soil data by process of automation. It has the capability to capture data non-destructively in lesser time. It uses remotely operated sensors and can save time and resources compared to conventional methods (Gehan and Kellogg 2017). For soil data, it allows for time-series measurements of soil nutrients and residue cover. It has a great advantage in its ability to take data of large areas with increased sample size for more accurate analysis. Increasing sampling points and frequency helps in quantifying the spatial and temporal variability of soil nutrients and residue cover. This quantification of variability is the basis of variable rate nutrient management for soil (Wollenhaupt et al. 1994). Variable rate management is one of the steps in precision agriculture (PA) which involves better management of farm inputs such as seed, fertilizers, agrochemicals, etc. (Mulla 2013). Technically PA involves facets of HT techniques such as spatio-temporally enhanced data collection and analysis management as well as technological advancements in computer processing, field positioning, yield monitoring, remote sensing, and sensor design (Mulla and Schepers 1997). Previous studies have shown that the profitability of variable rate management practices depends on the accuracy of soil test maps used to make nutrient rate and deficiency maps. Also, HT techniques are dynamic in nature, changing with advances in newer technologies. To create nutrient management maps, an array of proximal and aerial techniques such as soil surveys, stationary sensors, infrared photographs, satellite imagery, drone photogrammetry, and a variety of grid and cell-sampling schemes are involved (Wollenhaupt et al. 1994; Mulla and Schepers 1997). Therefore, in this review, technological advancements in HT techniques related to estimation of soil nutrients and residue cover are being discussed.

28.1.1 Proximal Sensing

Proximal sensing involves measurements with handheld or tractor driven sensors or stationary sensors embedded in soils. These sensors, also known as "on the go" are used for rapid assessment of soil properties such as organic matter, electrical conductivity, nitrate content, and compaction (Barnes et al. 2003). Therefore, proximal sensing is mainly based on electrochemical and electrical sensing instead of sensing electromagnetic radiation. The soil assessments are used for estimation of soil pH, nitrogen (N), phosphorus (P), potassium (K), soil texture, and cation exchange capacity (Bah et al. 2012; Mulla 2013). However, proximal sensing involves either placement of several stationary sensors or use of a single handheld or tractor driven sensor multiple times. This redundancy leads to proximal sensing being a low-throughput technology.

28.1.2 Remote Sensing

Remote sensing is non-contact measurement of electromagnetic radiation reflected or emitted from earth objects. It involves radiation measuring sensors mounted on ground-based vehicles, unmanned aerial vehicles (UAVs), or satellites (Campbell and Wynne 2011). The radiation measured by sensors vary based on the earth object such as soil, water, healthy vegetation, and stressed or dry vegetation (Fig. 28.1). Radiation reflected by bare soils is affected mainly by soil moisture and organic matter content, and to a lesser extent by clay minerals and calcium carbonate or iron oxides. For example, soils with higher moisture content absorb more NIR and appear darker than soils with lower moisture (Fig. 28.2). Each of the soil constituents reflect radiation of distinct wavelength from the electromagnetic spectrum, also known as spectral signature (Thomasson et al. 2001; Rossel et al. 2006). Based on the spectral signatures various methods have been developed for data acquisition, band selection, model estimation, and verification of remote sensing methods for soil organic matter, N, P, K, and residue cover measurements (Chen et al. 2011). Those methods include ground measured spectrum, high or low altitude sensing using aircrafts or

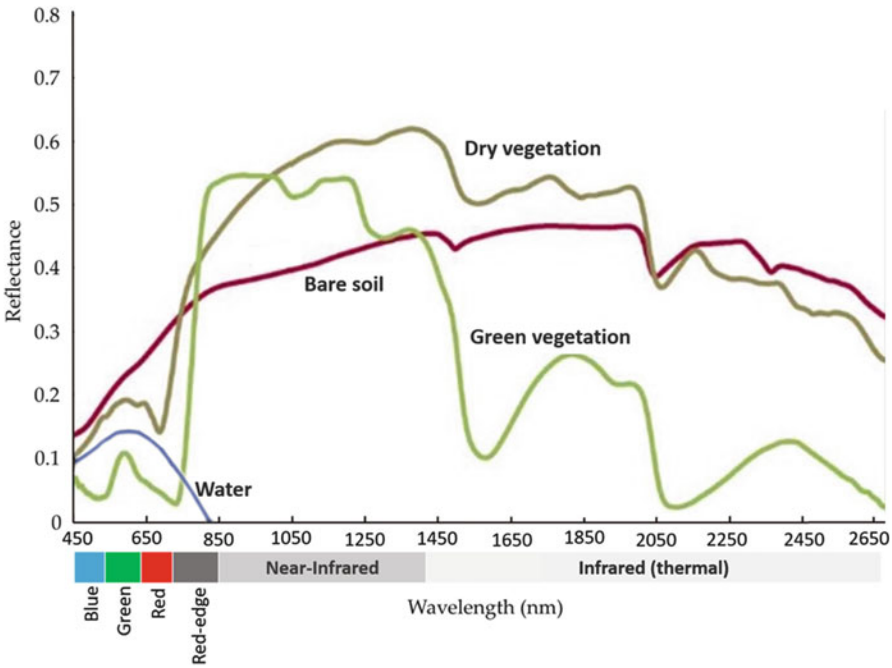

Fig. 28.1 Reflectance curves for green vegetation, dry vegetation, bare soil, and water for different radiations of electromagnetic spectrum. Blue, green and red belong to the visible spectrum whereas red-edge, near-infrared, and infrared belong to the invisible spectrum (Campbell and Wynne 2011; Mohamed et al. 2018)

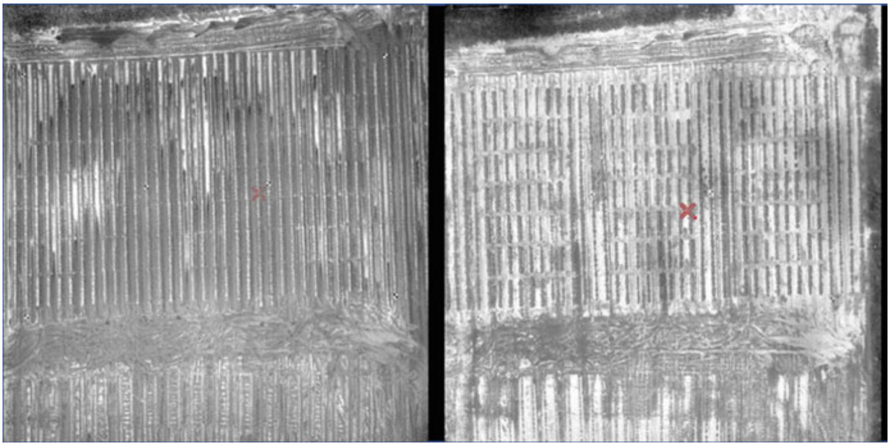

Fig. 28.2 Grey scale aerial images of two fields taken using Tetracam® ADC micro near-infrared (NIR) camera at Suffolk, USA. The image on the left was taken 1 day after rainfall whereas the image on the right was taken 17 days after rainfall on the same field. For both images, darker shades of grey represent lower NIR reflectance. The soil type of the fields is sandy loam, and the crop planted is groundnut (*Arachis hypogaea* L.) at 10 and 27 days after planting

drones, satellite multispectral or hyperspectral sensing, microwave and laser scanning, and LiDAR.

Among the methods developed, ground measured spectrum was initially convenient because of its low cost, flexibility, and application prospects (Stoner and Baumgardner 1981). Developed in the 1980s as a pioneer in soil remote sensing, ground measured spectrum could be used to detect and quantify soil organic matter with 60–87% accuracy (R^2 range from 0.60 to 0.87) (Krishnan et al. 1980). However, it was a redundant and low-throughput method and results could vary due to human error. This method was followed by satellite mounted multispectral sensor. The images received were of large acreages and were used to determine soil properties remotely in a mostly automated way. For example, one study estimated sand, clay, and soil organic carbon percentages using thermal infrared spectra with 30–70% accuracy (R^2 ranged from 0.3 to 0.7) (Sullivan et al. 2005). However, satellite images had coarse resolution (30–100 m pixel size) and multispectral sensors captured fewer wavelengths of the spectrum. Therefore, hyperspectral sensors were developed which measured several wavelengths from the spectrum.

The development of hyperspectral sensors also coincided with development of computers with powerful processors for iterative statistical analysis. Several studies were published which estimated soil organic matter, soil carbon content, and topsoil texture using soil reflectance from hyperspectral sensors (Selige et al. 2006; Gomez et al. 2008; Yu et al. 2015; Shen et al. 2020). The hyperspectral data was subjected to statistical analysis using stepwise multiple linear regression, partial least square regression (PLSR), multivariate adaptive regression splines, principal component regression, and artificial neural networks to derive soil nutrient estimation models.

Fig. 28.3 A MicaScence® Altum (MicaScence, Seattle, USA) multispectral sensor mounted on a DJI Matrice 200 (DJI, Shenzen, China) UAV. The sensor collects data in six bands (red, green, blue, red-edge, near-infrared, and thermal) simultaneously

The PLSR models could estimate soil carbon, total N, sand, and clay content in soil with over 90% accuracy (R^2 above 0.9). However, the problems with hyperspectral sensors owe to its high cost and large amount of data collected (Chen et al. 2011). Moreover, most of the hyperspectral sensors are either handheld or mounted on satellites and aircrafts. Sensors mounted on UAVs have barely been tested and are not economically and technically viable on a farm scale. Therefore, more research is required on UAV mounted hyperspectral sensors and the most feasible option right now is multispectral sensor such as a MicaSence®Altum mounted on an UAV (Fig. 28.3).

28.2 Spectral Characteristics and Remote Estimation of Different Soil Nutrients

28.2.1 Soil N Content

The basic premise for soil N content estimation using remote sensing is either indirect estimation by soil organic matter (SOM) determination or by estimating plant tissue N content (Scharf et al. 2002). It is a consensus that soil organic matter (and hence organic carbon) and soil moisture are mostly correlated to soil reflectance (Zheng and Schreier 1988). The utility of soil organic matter to estimate soil nitrogen is the assumption that N mineralization, and subsequently N availability to the growing crop, will be proportional to organic matter content. With spatially dense data obtained through remote sensing, a variable N application map that is a function of soil organic matter could then be developed. This assumption is based on previous studies which suggest that nitrate levels are higher in areas with high SOM (Blackmer and White 1998). However, several inconsistencies were found because availability of N from soil of known organic matter content can vary widely because of other soil characteristics, such as water content, pH, and dissolved organic carbon. These properties have a significant impact on N cycle processes including mineralization, immobilization, denitrification, and leaching (Scharf et al. 2002). Therefore, another method of indirect determination is detecting crop N status using remote sensing.

Nitrogen stress in plants negatively affects light-absorbing leaf pigments and tissue development in leaves. This causes higher reflectance in the blue and red band and lower reflectance in the NIR band (McMurtrey III et al. 1994; Blackmer et al. 1996; Beatty et al. 2000). However, a major drawback of these methods is the requirement of N by plants at a very early stage when pigments are not developed yet. This means by the time N deficiency is detected, addition of more N to soil would not result in economic yield. Also soil reflectance interferes with crop reflectance especially in the green and NIR bands (Daughtry et al. 2000; Clarke et al. 2001).

With recent advances in hyperspectral imagery and data management technologies soil nitrogen estimation model were created. A study used 11 bands from satellite imagery to derive 44 indices and all indices were used in regression kriging to develop prediction models (Xu et al. 2018). The study used stepwise multiple linear regression to model relationships between soil N and spectral indices, and kriging to fit the residuals, followed by Kolmogorov–Smirnov test for model calibration and validation. Though the model accuracy was low ($R^2 = 0.31$), the method is a breakthrough in HT estimation of soil nutrient research. More research is required in this direction, and big data management, machine learning, and artificial neural networks has to be included.

28.2.2 Soil P and K Content

Fewer studies have been done to estimate soil P and K using remote sensing. Most studies are extension of research on soil N content by using established methods such as the use of hyperspectral imagery to derive indices and train models with ground truth data (Kawamura et al. 2011; Rivero et al. 2009; Lin et al. 2015; Xu et al. 2018; Lu et al. 2020). The study by Kawamura et al. (2011) developed a relationship between 12 spectral indices derived from leaf reflectance with plant P and K content. The plant P and K content could further estimate soil P (Olsen P) and K (exchangeable K) fertility with significant accuracy (R^2 for $P > 0.89$; R^2 for $K > 0.73$). A recent study using hyperspectral bands to estimate leaf K content of rice yielded similar results ($R^2 = 0.74$) (Lu et al. 2020). The study using 44 spectral indices for soil N content was repeated for soil K. The best regression model could estimate up to 40% of the variation in soil K ($R^2 = 0.44$) (Xu et al. 2018).

Several studies have suggested that red, NIR, red edge leaf reflectance and their derived spectral indices are better for estimation of soil total P and Olsen P (Rivero et al. 2009; Lin et al. 2015). Therefore, with few conclusive studies on HTP estimation of soil P and K, there is no consensus on the methodology. Extensive studies are required in this area of soil science.

28.2.3 Soil Moisture

Many studies have shown decrease of soil reflectance with the increase of soil moisture content (Post et al. 2000; Galvão et al. 2001) (Fig. 28.4). This relationship is due to two reasons; soil particles covered with thin films of water and water on the lattice sites of some minerals present in the soil (Stoner and Baumgardner 1981). With the improvement of measurement tools, the change in spectral reflectance with change in soil moisture levels became more pronounced at longer wavelengths (>1,450 nm) (Weidong et al. 2002). The same study also showed that, at higher moisture contents (>40% VWC) the trend changes, and reflectance increases with

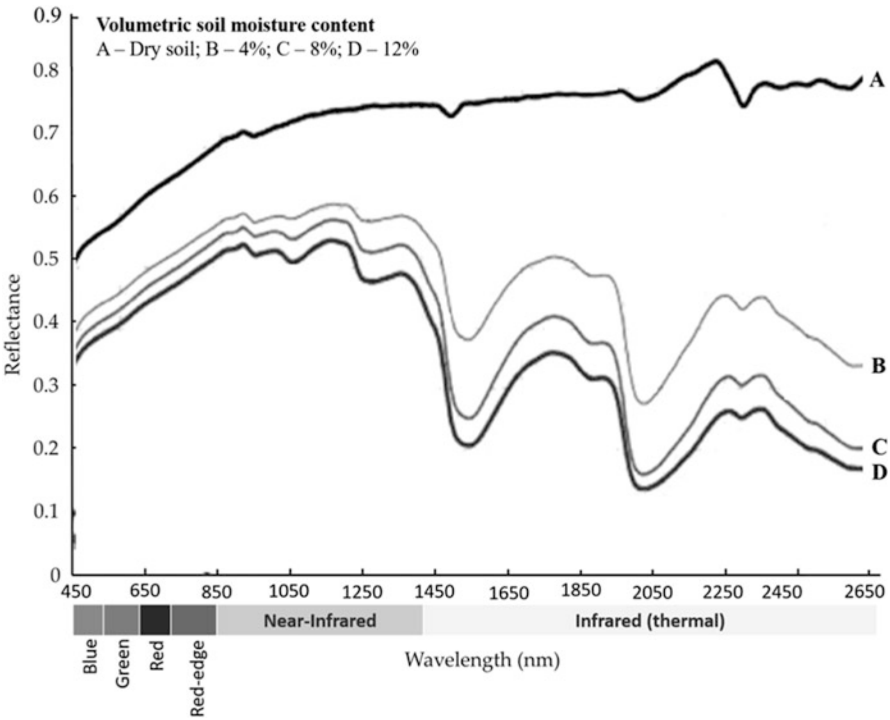

Fig. 28.4 Reflectance curves for different levels of soil moisture content (dry soil, 4%, 8%, 12% volumetric water content) within the electromagnetic spectrum. Blue, green and red belong to the visible spectrum whereas red-edge, near-infrared, and infrared belong to the invisible spectrum (Mohamed et al. 2018)

the higher moisture content. They determined this type of reversal to be somewhere around field capacity, while it changed for different soils, and happens before the point where water retention is saturating the reflectance signal. A study deriving soil moisture estimation models suggested that using degree of saturation instead of volumetric water content minimized the variation within soil types (Lobell and Asner 2002). The study also suggested that short wave infrared (SWIR) region of reflectance was better than visible-near-infrared (VNIR) as predictors for soil moisture estimation models.

28.2.4 Soil Organic Matter

Reflectance decreases with increase in SOM content (Fig. 28.5). Increasing absorption of visible light with increasing SOM give soils with higher organic matter a darker appearance. Studies on reflectance by SOM have shown that wavelengths of 570 nm, 850 nm, 1,150 nm, 1,680 nm, 2,190 nm, and 2,250 nm were highly correlated to SOM content (correlation coefficient above ±0.8) (Krishnan et al.

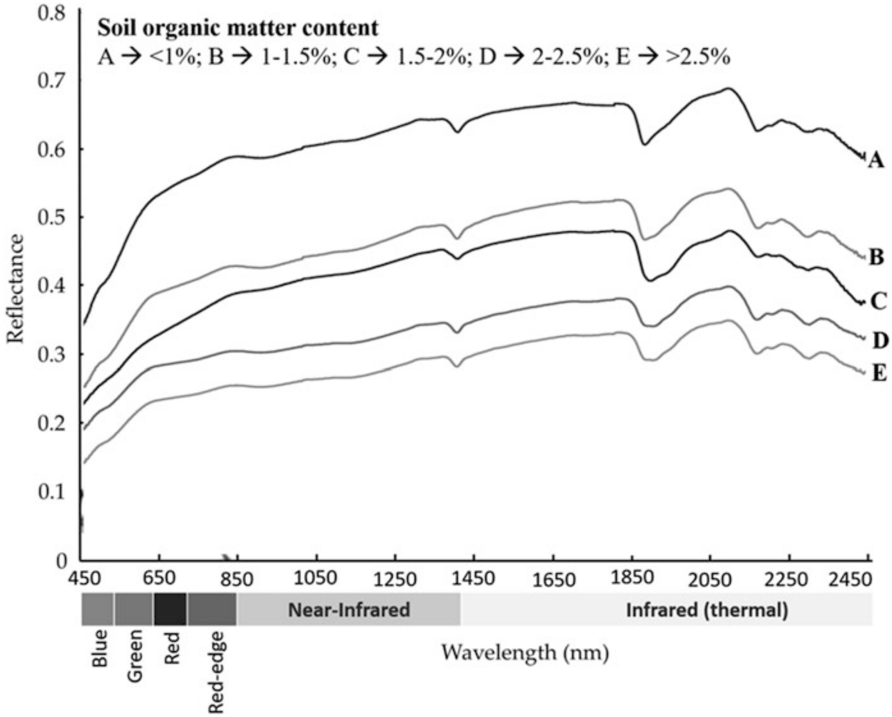

Fig. 28.5 Reflectance curves for different levels of soil organic matter within the electromagnetic spectrum. Blue, green and red belong to the visible spectrum whereas red-edge, near-infrared, and infrared belong to the invisible spectrum (Ding et al. 2018)

1980; He et al. 2009). Both studies also showed that log transformed reflectance values around 600 nm, 850 nm, 1,100 nm, 1,700 nm, and 2,200 nm form the best predictors for regression equations predicting SOM (R^2 values above 0.85).

The reflectance pattern of SOM is mainly dominated by organic carbon (OC) (Henderson et al. 1992). The OC in soils also masks the effect of other organic or mineral soil constituents causing OC, and hence SOM, dominant in the reflectance characteristics of soils. The same study also concluded that the cause for lower reflectance of SOM and OC is due to the optical properties of humic acid, which absorbs most of the electromagnetic spectrum. However, it was also found that differences in parent material of soils such as iron oxide content, and soil texture influenced reflectance curves of SOM. Therefore, more research is required to study different soils to derive universal regression models for SOM and OC estimation.

The soil OC is a key characteristic of soil quality which impacts the assortment of organic compounds and physical properties of soils (Carter 2002). The evaluation of greenhouse gas emissions from soils requires a precise information on the fate of carbon and nitrogen in soils. Reflectance of soil OC is also influenced by the degree of decomposition of organic fibers in soil (Stoner and Baumgardner 1981). The study found that partially and fully decomposed organic fibers had similar reflectance curves for organic soils. However, soils with minimally decomposed organic fibers had a distinct and different reflectance curves as compared to partially or fully decomposed organic fibers. Therefore, for soil nutrient classification, minimally decomposed and not decomposed organic fibers could be included under a separate category as soil residue.

28.3 What Is Soil Residue Cover?

The agricultural residues comprising of stalk, stem, leaves, and pods that remain on or beneath the soil surface after harvest is known as soil residue (Lal et al. 1998; de Decker 2014).

The soil residue cover serves several purposes:

- Enhancing soil fertility and productivity by maintaining and improving soil structure.
- Preventing soil erosion from rain and wind.
- Reduces irrigation runoff by holding most of the water in the soil.
- Prevents soil moisture loss due to evaporation.
- Provides a conducive habitat for soil fungi and fauna such as earthworm.
- Facilitates carbon (C) sequestration by holding organic matter in the soil.
- Supply subsequent crops with nutrients available in the residue such as N, K, and sulfur (S).
- They have shown to suppress weeds by acting as mulch.

Soil residue cover varies with the nature of crop and tillage practices. Cereal crops tend to have more soil residue than legume crops. Different tillage practices such as

Table 28.1 Percentage soil residue cover using different tillage practices (Shelton et al. 1995; de Decker 2014)

Tillage operation	Residue cover (%)	
	Cereals	Legumes
After harvest	90–95	60–80
Over-winter decomposition	80–95	70–80
Moldboard plow	0–10	0–5
Paraplow	80–90	75–85
Secondary tillage	50–75	30–60
Twisted point chisel	50–70	30–40
Straight point chisel	60–80	40–60
Disking (<9-in. spacing)	40–70	25–40
Disking (7–9-in. spacing)	30–60	20–40
Anhydrous applicator	75–85	45–70
Field cultivator	60–90	35–75
Row planter	85–95	75–95
No-till drill	55–75	40–60

no-till, disking, or chiseling can cause the residue cover to vary (Table 28.1). These practices are included under the broad term of soil residue cover management. Studies have suggested that soil residue needs to be managed year-round to provide the benefits without interfering crop production (Bradford and Huang 1994; Shelton et al. 1995; Flerchinger et al., 2003; Lampurlanés and Cantero-Martínez 2006). Therefore, crop residue management has become an integral component of conservation tillage systems for C sequestration. In fact, conservation tillage is defined in terms of percentage of soil residue present (>30% is threshold) (Daughtry et al. 2005). Therefore, measurement of soil residue cover is an important aspect of its management.

28.4 Manual Soil Residue Measurement

Soil residue cover has been measured proximally using manual filed techniques (Laflen et al. 1981). Visual intercept method involves using point or line intercept. In a line intercept the distance along a line covered by residue is observed whereas in a point intercept, residue cover is marked as present or absent at predefined points. Line transect and meter stick methods of measurement are based on line and point intercept (Morrison et al. 1993). Another method known as standing stubble method measures vertical aspect of the residue cover. Newer methods involve photography and videography of the field and visually estimating residue cover either on a percentage scale or number of occurrences. These types of measurements were time consuming and subject to human error. Laflen et al. (1981) found 6 to 10% overestimation of soil residue by line transect method. Though the variability in photography method was lower, the visual estimation was too subjective process. Therefore, newer more automated systems were developed such as sensor-based residue meters which could identify soil residue based on its reflectance and spectral properties (Daughtry et al. 1996).

28.5 Spectral Properties and Remote Estimation of Soil Residue Cover

The spectral properties of soil residue cover vary with soil and crop residue type as well as moisture content in it (Fig. 28.6). Though the variation is mostly in magnitude of reflectance, and the pattern is similar for all. The reflectance pattern of residue cover is similar to dry or dead vegetation (Fig. 28.1) (Quemada and Daughtry 2016). Dry residue had a broad absorption feature near 2,100 nm and is associated with cellulose-lignin, which is absent in soils. This selective band was used to develop cellulose absorption index (CAI) which could estimate residue cover accurately ($R^2 = 0.89$) (Daughtry et al. 2004). This estimation was further used to assess soil tillage intensity based on residue cover with 80–82% accuracy (Daughtry et al. 2006). Use of spectral indices and algorithm based on individual reflectance was found to be better than individual reflectance because the indices are resistant to time of the day, sun and view angles (Biard and Baret 1997).

Changes in physical and chemical properties of residue cover during decomposition could change their reflectance spectra and affect the ability of remote sensing methods to assess crop residue cover. This is because cellulose and hemicellulose in the plant residue decompose faster than lignin, causing a proportionate increase in lignin with time. This change in residue constituents changes its reflectance pattern (Daughtry et al. 2010). The same study also found that using narrow band for residue estimation was better than using broad spectral bands. Results showed that individual bands at 2100 nm and 2300 nm were minimally affected by the decomposition process and hence they should not be clubbed with other bands. Therefore, advanced multispectral sensors with a few appropriately positioned, relatively narrow (10–40 nm) bands or hyperspectral sensors are needed to reliably assess crop residue cover. Further studies have also shown the effectiveness of CAI along with other indices such as Lignin–Cellulose Absorption Index (LCA) and Normalized Difference Tillage Index (NDTI) (Serbin et al. 2009). This study also showed that soil spectral properties, and thus index values, were affected primarily by soil mineralogy and soil organic carbon content. It was also suggested that CAI could be used for monitoring tillage practices and subsequent C sequestration modeling.

However, there seems to be fewer studies on estimation of crop residue cover using UAV mounted hyperspectral and multispectral sensors. One recent study compared spectral indices from satellite imagery with UAV imagery (Raoufat et al. 2020). Results show that spectral indices derived using satellite imagery was better than that of UAV. However, the study used lesser indices derived from UAV sensors as compared to satellite. Moreover, the significant operating advantage of UAVs outweighs the slight accuracy using satellite imagery. The study also suggested that more research using drone sensors is required.

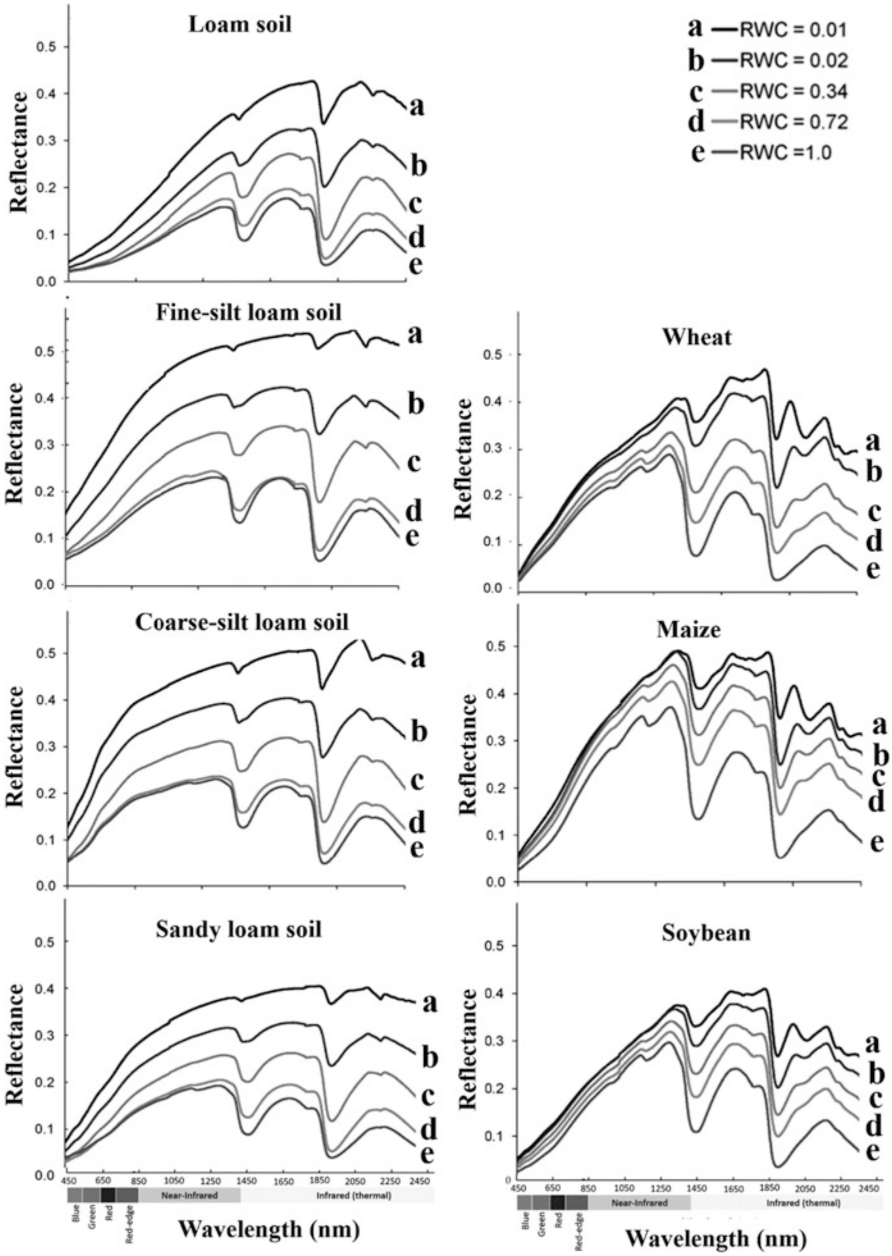

Fig. 28.6 Reflectance curves for soil residue cover within the electromagnetic spectrum over four soil types (loam, fine-silt loam, coarse-silt loam, and sandy loam), and of three crop residues (wheat, maize, and soybean) having different levels of relative water content (RWC*). Blue, green and red belong to the visible spectrum whereas red-edge, near-infrared, and infrared belong to the invisible spectrum (Quemada and Daughtry 2016). *RWC (%) = [(W − DW)/(TW − DW)] × 100, Where, W—sample fresh weight; TW—sample turgid weight; DW—sample dry weight

28.6 Using Soil Remote Sensing for Precision Agriculture

Precision farming has progressed through many stages. It began with farming by soil and progressed to site-specific soil management based on grid sampling and management zones. More recently there has been increasing emphasis on real-time on-the-go monitoring with fully automated aerial or ground based sensors (Mulla 2013). Since estimation of soil nutrients and residue cover is feasible using aerial remote sensing, they could be used to prepare high resolution nutrient and residue cover maps in real time. These maps could be used to determine rate of nutrient deficiencies which differ within different areas of the field. These deficiencies could be ameliorated by varying the rate of application among the deficient spots in the map (Sarkar and Jha 2020). This variable rate application is the basis of PA. New studies have outlined the efficiency of aerial remote sensing for faster and automated data collection and analysis (Sarkar et al. 2020; Sarkar and Jha 2020); Oakes et al. 2020; Sarkar et al. 2021). These studies have concluded that aerial sensors take significantly less time and personnel for data collection and analysis as compared to traditional methods.

28.7 Conclusion

Though HT estimation of soil nutrients and residue cover is feasible, it is a long way from PA. Focused research on sensor development and automated data management is required as of now. Several other challenges in hyperspectral imagery involve calibrating raw digital numbers to true surface reflectance, correcting imagery for atmospheric interferences and/or off-nadir view angles, and georeferencing images using GPS-based ground control points. More research is required for automation of these time consuming steps. The next step in PA would be direct and real-time estimation of nutrient deficiencies without using reference strips. This requires further research and development of spectral indices which can estimate multiple soil characteristics. UAVs are more user friendly and automated as compared to satellites and handheld sensors. Along with technological development in UAVs, data processing and statistical technics such as machine learning, computer vision, and artificial neural networks are also required. Faster and automated processing of data generated using UAV mounted hyperspectral sensor is the HT method required for estimation of soil nutrient and residue cover. This would save a lot of time and resources by avoiding over application of soil nutrients and faster decision making by growers, and faster and accurate measurements by soil scientists.

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Part III

Global Perspectives

Global Development in Soil Science Research: Agriculture Sensors and Technologies

29

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Abstract

The importance of soil resource to global food supply and climate change mitigation by carbon sequestration are the two most important factors for the constantly growing interest in global soil research. In view of its growing recognition as an important natural resource, the United Nations has declared 2015 as the "International Year of Soils" in the 68th Session of its General Assembly. With population increase, world hunger, water stress, and climate change, global crop production are continuously under stress to meet future demands. The global crop production will have to be doubled by 2050 to meet the population's projected demands. Thus, the pressure on soil resources is bound to increase and they need to be managed wisely. "If you can't measure it, you can't manage it." Assessing soil data is essential in monitoring soil attributes, evaluating changes related to soil quality, judging soil resources, and improving crop yields. The conventional soil analysis can provide accurate measurements for a limited number of samples due to the cost, time, and labor analysis, which leads to inadequate spatial field data and restricts the resolution of the prescription maps. The development of soil sensors and technologies can improve agricultural systems by providing a rapid, in situ, and innovative characterization and measurement of soil properties over current methods. In this chapter, we will explore the agriculture sensors and technologies used in precision agriculture, agribusiness and discuss how these tools can optimize crops and increase the world's capacity to feed future populations.

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Keywords

Soil resources · Soil sensors · Precision agriculture · Crop production · Soil mapping

Abbreviations

AI	Artificial Intelligence
Ca	Calcium
CEC	Cation exchange capacity
FDR	Frequency-domain reflectometry
GPS	Global positioning system
K	Potassium
Mg	Magnesium
N	Nitrogen
Na	Sodium
P	Phosphorus
SOC	Soil organic carbon
SOM	Soil organic matter
SWP	Soil water potential
TDR	Time-domain reflectometry
VFR	Variable fertilizer rate
Vis-NIR	Visible-Near infrared

29.1 Introduction

Agriculture feeds the globe. With population increase, world hunger, water stress, and climate change, global crop production is continuously under stress to meet future demands. As indicated by the researchers at the University of Minnesota, the global crop production will have to be doubled by 2050 to meet the population's projected demands (Ray et al. 2013). These researchers performed a study on the speculated crop production by 2050 using 2.5 million agricultural statistics. Their results showed that the global production of 4 key crops (rice, maize, wheat, and soybean) is below 2050 projected demands by 0.9–1.5% of the annual rate required to double global production by 2050 (Ray et al. 2013). Assessing soil data is essential in monitoring soil attributes, evaluating changes related to soil quality, judging soil resources, and improving crop yields. Soil data such as nutrients level, water content, compaction, pH, and salinity distribution are collected throughout the field by performing systematic soil sampling followed by laboratory analysis. However, these conventional tests can provide accurate measurements for a limited number of samples due to the cost, time, and labor analysis. This provides inade-quate spatial field data and restricts the resolution of the prescription maps

(Dobermann et al. 2004). Hence, the development of soil sensors and technologies has the opportunity to improve agricultural systems through providing a rapid, in situ, and innovative characterization and measurement of soil properties over current methods. By deploying sensors and mapping soil properties, farmers can have a better understanding of their crops, reduce stresses on the environment, and make more precise decisions. This is where precision agriculture and farm automation technologies play great roles (Adamchuk et al. 2005; Hunt Jr and Daughtry 2018; Kanjilal et al. 2014). In this chapter, we will explore the agriculture sensors and technologies used in agribusiness and discuss how these tools can optimize crops and increase the world's capacity to feed future populations.

29.2 Precision Agriculture Overview

Precision agriculture is defined as a group of farmer practices done to achieve agricultural sustainability. These practices are based on the four Rs: right place, right time, right amount, and right application. Precision agriculture provides site-specific management of agriculture inputs to preserve the environment, enhance product quality, and increase crop yields. Sensors data have been used in precision agriculture to correct soil pH, generate fertilizer and watering recommendations, manage weed, control pests, and provide information on precise positioning, and other soil properties like compaction, air permeability, and temperature. Precision agriculture companies are attracting more farmers towards more flexible and faster startups that are capable of systematically maximizing crop yields.

29.2.1 Agricultural Sensors for Soil Chemical and Physical Properties

Several sensing technologies exist in precision agriculture to provide data that can help farmers in optimizing their crops and monitor different soil properties. Soil properties can be divided into two categories: chemical and physical. Soil chemical properties include pH, total carbon, total nitrogen (N), available phosphorus (P), sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), heavy metal concentration, cation exchange capacity (CEC), and soil electrical conductivity (Brady et al. 2008). While soil physical properties include texture, color, porosity, density, air, and temperature (Brady et al. 2008).

29.2.1.1 Electrochemical Sensors

The physical nature and the chemical properties of soil determine its fertility. Soil fertility is crucial in determining the soil's ability to supply plant nutrients in enough amounts and proportion for plant growth. Crop production removes nutrients from the soil. Hence, sustainably reapplying plant nutrients is essential for optimum crop yield and environmental safety. Nutrients sensors are used to quantify the concentration of macronutrients and micronutrients in soils and monitor fertilizer application in soil accordingly. Electrochemical sensors are most commonly used to detect specific ions in soils. Electrochemical sensors function by relating electricity to chemical reactions and are broadly divided into three types: voltammetric, potentiometric, and conductometric (Veloso et al. 2012). They provide key information on soil pH, nutrients levels, heavy metal concentration, and electrical conductivity (Table 29.1).

29.2.1.2 Dielectric Sensors

Developments in soil moisture sensors have permitted real-time continuous soil water measurements. Soil moisture sensors can measure soil water data and be downloaded wirelessly within a certain radio range making the data acquisition easier for growers (Ganjegunte et al. 2012). Dielectric sensors are commonly used to measure the soil moisture content by measuring the electrical charge-storing capacity, referred to as dielectric constant, of the soil. Time-domain reflectometry (TDR), frequency-domain reflectometry (FDR), and capacitance (Table 29.1) are different kinds of dielectric soil moisture content sensors that are used directly in soil (Veldkamp and O'Brien 2000; Dean 1995; Ledieu et al. 1986). Soil water potential (SWP) is another basic parameter that describes the state of water in the soil. Soil water potential determines how water moves from the soil to the plant. SWP sensors function by measuring the dielectric permittivity of a solid matrix of porous ceramic discs and are used directly in soil (Malazian et al. 2011).

29.2.1.3 Mechanical Sensors

Soil compaction can be caused by the heavyweight of field equipment or by natural soil-forming processes, which causes soil particles to press together reducing pore space between them. This can cause soil degradation, increases root penetration resistance, and negatively affects crop production (Adamchuk et al. 2004). Mechanical sensors are used to measure soil compaction or mechanical resistance. These sensors evaluate soil compaction by measuring resistance forces resulting from cutting, breaking, and displacing of soil (Adamchuk and Rossel 2010). A standard vertical cone penetrometer is the most conventional method to measure soil resistance with depth at a given location, directly representing soil compaction (ASABE Standards 2006). Single-tip horizontal sensors are a different kind of mechanical sensors that are used to measure horizontal soil penetration resistance at specific depths. In addition to tip-based sensors, instrumented tine sensors are also used to measure the vertical distribution of soil compaction.

29.2.1.4 Acoustic and Pneumatic Sensors

Acoustic and pneumatic sensor measurements can be correlated to compaction; thus, they may be used as alternatives to mechanical sensors. Acoustic sensors are used to determine soil texture and structure by measuring the change in noise level as the tool interacts with the soil particles (Adamchuk and Rossel 2010). Microphone equipped soil shank and Microphone equipped horizontal cone penetrometer are two types of acoustic sensors that use frequencies to distinguish between different types of soil and detect compaction layers (Liu et al. 1993; Grift et al. 2005; Brady et al. 2008). Pneumatic sensors measure soil–air permeability, which is the pressure

Table 29.1 Summary of precision agricultural sensors for soil chemical and physical properties

Type of sensors	Functions	Examples of applications	References
Electrochemical	Detects specific ions in the soil	• Potentiometric ion-selective electrodes for N, K, Na, and pH • Cyclic voltammetry using carbon-based electrodes for P and iron minerals • Conductometric soil salinity/ electrical conductivity meter	Adamchuk et al. (2005), Memon et al. (2009), Zeitoun and Biswas (2020), Nagamori et al. (2007)
Dielectric	Measures dielectric constant in the soil to quantify soil moisture and SWP	• TDR for soil moisture content • FDR for soil moisture content • Capacitance for soil moisture content • Dielectric permittivity sensor for SWP	Ledieu et al. (1986), Veldkamp and O'Brien (2000), Dean (1995), Malazian et al. (2011)
Mechanical	Measures soil compaction or mechanical resistance	• Vertical cone penetrometer for soil compaction • Single-tip horizontal sensors for soil compaction • Instrumented tine sensors for soil compaction	ASABE Standards (2006), Adamchuk and Rossel (2010), Adamchuk and Rossel (2010)
Optical	Measures soil properties	• Vis-near infrared spectroscopy for soil erosion mapping, weed mapping, and SOC	Felton and McCloy (1992), Sepuru and Dube (2018)
Pneumatic	Measures air permeability of the soil	• air pressure transducer sensor for soil compaction	Clement and Stombaugh (2000)
Acoustic	Measure soil texture and structure	• Microphone equipped soil shank sensor for differentiating between soil types • Microphone equipped horizontal cone penetrometer sensor for soil compaction	Liu et al. (1993), Grift et al. (2005)

needed for air in a pore space to collapse into the soil at a given depth (Madhumitha et al. 2020). Air pressure transducer can be used to measure air pressure and flow to estimate soil compaction (Clement and Stombaugh 2000).

29.2.1.5 Optical Sensors

Optical sensors employ electromagnetic energy to characterize soil properties. They use various frequencies of light reflectance in visible (400–700 nm) (Viscarra Rossel et al. 2008), near-infrared (700–2500 nm), or/and mid-infrared (2500–25,000 nm) to perform soil analysis (Adamchuk and Rossel 2010). These sensors can be placed on vehicles or drones which can detect the level of energy absorbed, reflected, or transmitted by soil particles in real time. Optical sensors can gather multiple data with just a single scan, which provides an opportunity to determine many soil properties such as soil organic matter, soil texture, weed management, mineral composition, and particle size (Shonk et al. 1991; Sudduth and Hummel 1993, Shibusawa et al. 2001, Mouazen et al. 2005, Christy 2008, Sui et al. 2008).

29.3 Sensor Output Applied

Sensors data are implemented and processed in precision agriculture to provide site-specific management of agricultural inputs, improve product quality, increase crop yield, and increase crop production profitability while minimizing environmental effects. Precision farming takes advantage of these data in different ways. Due to the increasing costs of fertilizers production inputs of soil macronutrients (NPK) (Sinfield et al. 2009) and water eutrophication associated with N and P fertilizers losses (Stelzer and Lamberti 2001; Brady and Weil 1996), optimizing plant yield while minimizing consumption and application of fertilizers is highly encouraged in agricultural practices. **Variable fertilizer rate (VFR)** management of macronutrients (NPK) is one of the most promising strategies for precision agriculture to optimize fertilizers use and crop yields (Sawyer 1994).VFR application tools integrate different layers of spatial field data to develop application algorithms. Commonly, soil nutrients distribution throughout the field is estimated by performing systematic soil sampling followed by laboratory analysis. However, the high cost of soil sampling and laboratory analysis limits the resolution of the prescription maps and provides inadequate spatial field data (Dobermann et al. 2004). On-the-go mapping system provides a promising fast and cost-effective alternative that uses electrochemical sensors to quantify macronutrient levels.

Soil pH is a key component of crop productivity and nutrient availability in soil (Brady et al. 2008). On-the-go electrochemical soil pH sensors are used to provide spatial variability of pH in the agriculture field, **soil pH mapping** (Schirrmann et al. 2011). These data are used to make decisions on applying alkaline or acidic fertilizers to control the pH of the soil and manage the effects of extreme soil pH conditions.

Soil salinity is one of the major concerns in agriculture. It can cause soil erosion and negatively affect plant growth and yield. In the past few decades, **soil salinity**

mapping has been an active area of research particularly for agricultural soils (Abuelgasim and Ammad 2019). Electrical conductivity measurements are used to perform soil salinity mapping. These measurements are used to conduct the soil salinization performance index. To control and mitigate soil salinization, beneficial management practices are undertaken to reduce excess salt movement through appropriate soil water management (Government of Canada 2020).

Soil moisture and SWP data are used to conduct soil water retention curves used to calculate plant-available water and estimate crop water requirements to manage **irrigation scheduling** (Bittelli and Flury 2009). Irrigation scheduling is applied in agriculture to avoid over/under irrigation which provides a great potential to use water efficiently, reduce the amount of nutrients leaked into the groundwater, and promote water supply conservation practices (Ganjegunte et al. 2012). Soil water retention curves are also used in **hydrological models for flood and drought risks** to enhance hydrological processes like ponding, evapotranspiration, and interception (Collentine and Futter 2018; Burek et al. 2012).

Increased soil compaction has adverse effects on agriculture and the environment. It has shown to negatively impact soil structure, increase runoff and soil erosion, reduce crop production, and cause land degradation (Hemmat and Adamchuk 2008; Alaoui and Diserens 2018). **Soil compaction mapping** can help to pinout where exactly the soil compaction occurs and toidentify suitable mechanical, chemical, or biological recommendations to control soil compaction. Tip-based and tine-based mechanical sensors are two powerful sensors that are capable of mapping spatial and vertical variation in soil compaction (Hemmat and Adamchuk 2008).

Optical sensors data provide a good source of information for **soil weed mapping** to help create proper site-specific weed management programs. One of the commercially available optical weed sensors is called WeedSeeker, which was developed by Felton and McCloy (1992). It uses visible and NIR reflectance to differentiate between green plants (weeds) against a background of soil and dead plant materials (Wang et al. 2001). Most agricultural fields are spatially variable in weed infestation; however, herbicide applications assume that weeds are distributed uniformly (Wang et al. 2001). This causes excess herbicide use and major problems down the road, such as herbicide-resistant crops (Green 2012). Mapping out the distribution of weeds using optical sensors data is very powerful in site-specific management of herbicide inputs and improves the efficiency of herbicide application to weed-infested sites. Optical sensors data can also be used for **soil erosion mapping**. Soil erosion is a serious global problem that affects soil conditions and crop production (Teng et al. 2016). About 75 billion tons of fertile soil is lost globally from agriculture systems per year (Sepuru and Dube 2018). Spectral indices (based on soil reflectance) such as coloration index and brightness index can be used to characterize soil-surface state (El Jazouli et al. 2017). By mapping and evaluating soil erosion risks, soil scientists can undertake effective management practices in reducing soil erosion rates. Few examples of commercial optical sensors used in soil erosion mapping are ASTER, Landsat8, and Sentinel2 (Shoshany et al. 2013; Vrieling et al. 2008). Multispectral sensors data are also used in **soil organic carbon (SOC) mapping** which is essential in assessing the sustainability of soil cultivation and understanding the effects of agriculture practices on SOC level in soils (Žížala et al. 2019). **VFR** application tools also use optical surveys of plant health determined by fluorescence sensing to detect nutrient stresses (Liew et al. 2008).

29.4 Artificial Intelligence in Agriculture

With climate change and population increase, artificial intelligence (AI) is developing in the agriculture industry to improve and protect crop yield. In the last 5 years, AI startup companies (Table 29.2) in the agriculture sector have raised over $800 M (CBINSIGHTS 2017). Some of the major ways that AI is contributing to agriculture are farm automation robotics, driverless tractors, satellites, and drone high-quality imaging (Table 29.2).

Farm automation is a fairly new technology that makes farms more efficient by automating the crop production cycle (Kanjilal et al. 2014). Farms need a lot of labor. Farm automation can make farming faster and easier, leading to a moderate amount of labor and more agricultural growth. Robotics innovations towards automatic watering, robotic harvesters, and seeding robots are developed to perform farmer's mundane tasks addressing major issues like labor shortage and rising global population (Kanjilal et al. 2014). The integration of these technologies with the farm environment can provide safety, convenience, quality, and energy efficiency benefits. **Driverless tractors** use mobile on-the-go sensor platforms with a global positioning system (GPS) and radar to accurately and quickly sample and characterize soil properties in the field (Adamchuk et al. 2004). This is used in soil management practices to collect soil data for VFR management. **Drones technology** has opened a plethora of unprecedented data opportunities towards collecting data and information for entire fields. Drone technology can capture high-quality imaging that are processed by machine learning and computer vision algorithms. These can be used to monitor crops, scan fields, identify crops and their health and ripeness, provide real-time estimates of crops' needs for water, fertilizer, or pesticides, and collect necessary agricultural data (Puri et al. 2017). **Satellites** and drone images are

Table 29.2 Summary of artificial intelligence technologies used in agriculture

Type of technology	Functions/company	References
Drones	• Field data collection/SkySquirrel technologies, Sensurion, PrecisionHawk, GeoVisual	CBINSIGHTS (2017)
Robotics	• Farm automation for watering, harvesting, and seeding/ Harvest CROO robotics, Clearpath robotics, and abundant robotics • Driverless tractors for soil sampling and analysis/Case IH, New Holland, Resson, Farmbot, and Blue River Technology	CBINSIGHTS (2017)
Satellite imaging	• Crop health monitoring/FarmShots, OmniEarth, Orbital Insight, Descartes Labs • Predictive analytics / aWhere, ec2ec, and optimal	CBINSIGHTS (2017)

processed and analyzed using machine learning algorithms for crop health monitoring and predictive analytics. The algorithms can be utilized to classify soil data, detect diseases, pests, and plant nutrients need in farms. Predictive analytics uses machine learning models with satellites to predict weather conditions like wind speed, temperature, precipitation, and solar radiation. All are conditions that affect crop productivity (Zhang and Kovacs 2012).

29.5 Global Implication

Food demand is expected to increase anywhere between 59% and 98% by 2050 (Valin et al. 2014), which will have a significant effect on food security. This and other trends including climate change and urbanization make this issue more challenging. To reverse this situation, an enhanced application of agricultural technologies in research is required.

According to the Food and Agriculture Organization of the United Nations, from the 570 million global farms, 87% of them are operated by smallholder farms (Lowder et al. 2016). More than 80% of the food is grown on such farms for human consumption and livestock (Graeub et al. 2016). In China, the Ministry of Science and Technology planned the National Agricultural Science and Technology Project that plans to supply food to 1.6 billion people by the mid-twenty-first century by supporting research on agriculture science and technology such as implementing precision agricultural practices. (Maohua 2001). Precision agriculture technologies are believed to create less adverse environmental consequences by targeting inputs such as chemicals and fertilizers where needed and reducing the loss of nutrients from the excess application (Norton and Swinton 2000). A study in Germany conducted by Schmerler and Jurschik (1997) determined their nitrogen fertilizer savings by comparing site-specific fertilization to uniform fertilization on winter wheat and spring barley and found savings of 5–15% along with higher yields. Another study examined VFR technology on corn in Ontario, Canada, and found between 4 and 36% reduced nitrogen leaching (Thrikawala et al. 1999). Similarly, Saleem et al. (2014) also reported a 40% reduction in fertilizer application using VFR technology compared to a standard uniform rate method and also noticed a significant reduction in total phosphorus and inorganic nitrogen losses in surface runoff. They concluded that VFR application could potentially improve crop productivity and reduce production costs (Saleem et al. 2014). Hoskinson et al. (1999) found that application using VFR technology reduced fertilizer cost by 30 to 40% on wheat in Idaho, USA.

Precision agriculture has also shown promising results in pesticide reduction. It is estimated that over 26 million metric tons of pesticides are used worldwide, some that are shown to persist in the environment resulting in contamination in groundwater, surface water, air, and soil (Abit et al. 2018). Using site-specific management to control weeds could reduce herbicide use by up to 100% (Abit et al. 2018). A four-year study on site-specific weed control found reduced herbicide use of maize, sugar beets, and wheat in Germany (Gerhards II 1999). Timmermann et al. (2003) also conducted a four-year experiment in five fields of wheat, barley, sugar beet, and corn (in Bonn Germany), and found an overall reduction of insecticide savings by 54%. They also noticed a decrease in environmental damage, due to less water contamination from herbicides (Timmermann et al. 2003). Abit et al. (2018) also reported similar studies in site-specific weed control, which allowed herbicide savings of up to 20–44%. Also, precision agriculture has shown some promising results for water management. About 40% of the world's total food is cropped on irrigated lands, and in the USA alone about 80% of the nation's consumptive water is used for irrigated agriculture (Abit et al. 2018). Variable rate irrigation (VRI) is the site-specific management of water where individual parts of a field receive the appropriate amount to overcome water stress (Abit et al. 2018). Studies have shown that implementing VRI systems on agricultural land may reduce water use by 8–20% (Sadler et al. 2005). Furthermore, reducing water use can also reduce energy requirements by less pumping and therefore reduction in energy-related CO_2 emissions (Abit et al. 2018). For example, Hedley et al. (2010) found energy savings of 23–67 CO_2-eq ha^{-1} per yr. in dairy pasture, corn, and potato fields.

Adopting precision agriculture technologies depend upon many factors such as farm size and condition, affordability and expected profit from the technology, skill and knowledge of farmer, family structure and government policies. Further, the adaptation level varies with countries and their geographic regions (Say et al. 2018). The GDP of developing nations largely depend upon their agricultural sector (Jaiswal et al. 2019) and thus provide a great challenge to implement PA in these parts of the world. The yield monitoring and variable rate (irrigation and fertilizers) were most used method across developing nations in recent years. The auto guidance system for sowing, spraying, and harvesting is slowly getting popularized across Argentina, Brazil, India, South Africa, Turkey, and other developing nations. In summary, agricultural sensors and technologies provide significant potential for crop management and provide environmental benefits such as a decrease of greenhouse gas emissions and pollution caused by fertilizers and pesticides as well as water and energy reduction. Ensuring worldwide food security lies in scientific knowledge and technology. Developing agriculture precision techniques will help lead the way into modern agriculture practices, which will take on challenges such as food security worldwide.

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Soil Science Research and Development in Latin America and the Caribbean

30

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Abstract

Soils of Latin America and the Caribbean have been studied for hundreds of years since ancient civilizations. However, formal studies on soil science started at the beginning of the twentieth century as part of agricultural sciences. The importance of studying soils of the region relies on their capacity to provide ecosystem services. These services are translated into food, water resources, climate regulation, and nutrient cycling. With a changing climate and human-induced transformations to our ecosystems, the provision of ecosystem services will be dependent on meaningful actions taken by governments, industries, and individuals. These actions need to be in the form of strategies aimed at erosion control, soil health enhancement, and sustainable soil management practices. Moreover, given the diversity of ecosystems in the region, research focused on the monitoring and improvement of soil health will be essential for Latin America and the Caribbean.

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30.1 Brief History of Soil Science in Latin America and the Caribbean

Soil science in Latin America and the Caribbean (LAC) developed mostly in tandem with agricultural sciences. At the beginning of the twentieth century, many countries in LAC started to pay more attention to the conservation of soil resources. The Soil Science Society of Latin America (SLCS) was founded in 1962 in Mendoza, Argentina, year in which the first World Congress Soil Science was held. The development of a scientific society focused on soil science was promoted in 1945 by the Interamerican Institute of Agricultural Sciences (IICA) and the Organization of American States (OEA). These organizations also considered that proceeded by the creation of a Latin American society, every country should create their national soil science societies if those were missing. Even before the creation of the SLCS there was already a strong interest in soil-related studies among agricultural research societies in the 1950s. This interest led to the creation of national soil science societies in Brazil (1947), Colombia (1955), Venezuela (1955), Argentina (1960), and Peru (1960), however in some countries the continuity of these societies was difficult due to the lack of resources (PlaSentis 2016).

The study of soils, however, has been reported before the establishment of formal science societies. That is the case of Brazil and Mexico. In Brazil, first land reports and rudimentary descriptions of soil can be dated back to the seventeenth and eighteenth century. However, more importance was given by the middle of the nineteenth century, as problems emerged in coffee and sugarcane plantations, essential products for the local economy. To tackle those problems, agricultural and chemical sciences merged to do research on soil fertility and plant nutrition. Additionally, agricultural institutes and agronomic stations were created between 1859 and 1888 in different parts of the country (Camargo et al. 2010).

According to Camargo et al. (2010), after 1889, soil science was integrated in new agronomy schools founded in the beginning of the twentieth century, especially courses focused on agriculture, chemistry, and mineralogy. It was until 1928 that the first Soil Department was formed at the Superior School of Agriculture and Veterinary Medicine in Viçosa. In terms of research, the Chemistry Institute (1918), later Agricultural Chemistry Institute (1934) focused on soil analysis and fertilization practices. The task of mapping Brazilian soils was carried out by the Soil Committee of the National Service of Agronomic Research in 1943. This Soil Committee organized in 1947 the first Brazilian Congress of Soil Science which led to the creation of the Brazilian Society of Soil Science.

For Mexico, traditional soil knowledge has a long history. Archeological research showed that pre-Hispanic cultures had a developed system of soil classification. However, formal studies on soil started at the beginning of the twentieth century after Mexican Revolution when agricultural development was crucial. With the aid of the researchers from the University of California, the National Commission of Irrigation was created in Mexico. With this Commission, Mexican technicians were trained to classify soil and elaborate maps for irrigation purposes. Of special importance was the Agrological Congress in 1928, regarded as the first National

Congress of Soil Science in the country. In this meeting, many aspects related to the study of soils and the importance of laboratory analyses were highlighted, however, none of them were achieved (Ortiz-Solorio 2010). The first educational programs focused on the study of soil initiated in 1937 at the National School of Agriculture, formally established in 1954. Since then other institutions have contributed to the education of soil science across the country (Ortiz-Solorio 2010).

30.2 Land Resources: An Opportunity for Agricultural Production and Environmental Protection

Latin America and the Caribbean is a privileged region in the world as it holds valuable land resources, relatively low population density, and potentially available land for agricultural production, mainly in South America. Total land accounts for more than 2 billion hectares divided into 34 countries, a population of 657 million people by 2018, which makes available 0.34 ha per capita in the region (OECD and FAO 2019a, b). Agriculture in the region occupies 38% of the land available (28.5% for pastures and 9.5% for crops), whilst forests cover 46%. Representing 15% of the world's surface, LAC receives 30% of precipitation and generates around 33% of the earth's water. Due to its great environmental diversity, the region not only possesses an enormous reserve of arable land and forests, but also one of the most complex farming systems in the globe (OECD and FAO 2019a, b). Although more than 90% of the cultivated area in LAC is regarded to be highly suitable for agriculture (OECD and FAO 2019a, b), it is well known that the region also has major degradation issues such as loss of soil fertility, salinization, erosion, and overall soil degradation (FAO and ITPS 2015).

Erosion is probably the biggest problem faced by LAC, as close to 20% of its soils are at risk (OECD and FAO 2019a, b). To give an idea, in Argentina, erosion puts pressure on 25 Mha, the country also faces big economic losses due to salinization in humid plains. The percentage of territory affected by erosion in different countries are as follows: 19% of Mexico's area, 75% of El Salvador's, 43% of Cuba's, 50% of Ecuador's, and 30% of Uruguay's. Central America's agriculture makes erosion favorable as large regions are located on hillsides. Another major issue is desertification, it affects 12% of Guatemala's territory, 17% of Colombia's, 28% of Ecuador's, and 62% of Chile's (FAO and ITPS 2015). Even though many soil degradation problems could be attributed to natural causes such as rainfall and wind, human activities like land clearing, overgrazing, and unsustainable management practices play a major role.

According to the FAO (2020), LAC has the largest reserve of arable land in the world. Around 28% of the world's potential new arable land is expected to be in the region (The World Bank 2013). As it can be seen, in the last 50 years (1961–2011) more arable land has become available in the region, changing from 561 to 741 million hectares. This trend has particularly impacted countries in South America.

The capacity of Latin American and Caribbean soils relies on two important factors: their ability to produce food for an increasing population and the plethora of ecosystem services they provide. First, agricultural production plays an important role in the region as it contributed to an average of 4.7% of the GDP in 2015–2017 (OECD and FAO 2019a, b). Currently, Latin America and the Caribbean accounts for 14% of global agricultural production, however, it is expected that by 2028 the region will provide more than 25% exports to the world (OECD et al. 2019a, b). Consequently, LAC's ability to supply the world with agricultural products is of utmost importance to food security. Nevertheless, increase of production is normally explained by an excessive use of inputs that put in risk soil and water, decreases biodiversity, promotes land use change, and undermines the livelihood of individuals. In this sense, it is crucial to ensure more sustainable ways of production that are responsible with the environment while at the same time contribute to social development in rural areas. Constant monitoring of soil resources, extension programs dedicated to expanding farmers' understanding of soil sustainable management, and applied local research could provide better answers to an uncertain future scenario.

Additionally, some of the many ecosystem services provided by soils in the region include nutrient cycling, habitat for organisms, water purification and contamination reduction, climate regulation and provision of food, fiber and fuels (Gardi et al. 2014). A major threat to these services is posed by deforestation. When these land use changes happen, it affects climate regulation through the carbon and nitrogen cycles (especially in the Amazon Basin); water regulation through changes in water quantity and quality, accompanied by erosion; and loss of biodiversity (FAO and ITPS 2015; Viglizzo and Frank 2006). Therefore, it is significant to create strategies aimed at the conservation of soil and ecosystems resources to decrease the impact of human activities.

30.3 Soils of Latin America and the Caribbean in Face of Climate Change

Climate change is probably the biggest challenge that humanity is facing and will face in this century. Even when LAC's contribution to greenhouse gas emissions, that accelerate climate change, is relatively low, accounting for 13%, significant actions need to be taken to decrease the pressure put on the region. This pressure is augmented by land use change and the emissions related to this practice (PNUMA 2010). The impact on the LAC region is diverse as different conditions are presented; however, major effects include high vulnerability in the agricultural sector, increase of arid zones, water scarcity, biodiversity loss, and damage to ecosystem services (Comision Europea 2013). According to the PNUMA (2010), the projected changes in meteorological events are: increase in the intensity and frequency of hurricanes in the Caribbean, change in the distribution patterns and intensity of precipitations, temperature changes, drought risk increase in coast areas close to the South Atlantic Ocean, and retreat of glaciers in the Patagonia and Andean regions.

Soil resources will face increased degradation and desertification due to the abovementioned modifications in several atmospheric events such as rainfall patterns and evapotranspiration rates. This soil degradation, which can be understood as the lack of biological or economic productivity of land, is mainly attributed to the effect of simultaneous changes like deforestation, conventional agricultural practices, and poor waste treatment. Consequently, soil depth, organic carbon content, pH, salinity, and fertility are the main physical and biochemical properties affected. Climate change will cause soil degradation in forms that include soil erosion and compaction, landslides, floods, and mineralization of organic matter (Gardi et al. 2014).

Available data on the possible effect of climate change on LAC soils has been developed by Comision Europea (2013). However, data and methods used vary considerably between countries, contingent upon resources available and diverse viewpoints to address the problem. Certainly, more studies are needed to better predict the potential impact of climate change on soils of the region.

Currently, soil degradation represents a serious issue in all LAC countries. For instance, soil desertification affects 35% of the region, around 6.9 million km^2 in different types of arid environments. On the other hand, in humid zones, deforestation is the major challenge to face as it affects 6.5% of the territory (1.3 million km^2). Almost half the territory, 49%, is exposed to water erosion, whilst around 56% LAC's land area is affected by chemical soil degradation, such as acidity and salinity (Comision Europea 2013).

Regarding the impact of climate change on the region, the A2 scenario projected by IPCC shows that soil's conditions will fluctuate between very dry areas and very wet in others. It is expected that a great proportion of LAC's land will turn into drier zones, although most of the total area will not be affected by large changes. According to the A2 climate change model, 21% of the total surface, around 4.1 million km^2, will become more arid, while only around 2% convert into wetter conditions, 298, 000 km^2 approximately (Gardi et al. 2014). Nonetheless, the addition of data is of utmost importance to better predict the impact of a changing climate in LAC.

30.4 Strategies for Sustainable Soil Management

In face of a changing climate, it is very likely that water scarcity will become a more serious problem as arid regions expand, and that food security will be more difficult to achieve in areas where the climate gets hotter and precipitation events become less common (Lobell et al. 2011). In already highly populated countries, the impact of climate change will be unpleasant, while for those that are already experiencing climate-related issues, the change will be disastrous (Miranda et al. 2011).

Meaningful changes are needed to enhance land's productivity and at the same time consider environmental conservation, or at least reduce the impact of human activities as much as possible. Some practices that meet these requirements are agroforestry, conservation agriculture (CA), precision agriculture (PA), and erosion control methods.

According to the USDA (2019), agroforestry is “the intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits.” Agroforestry represents a great opportunity for LAC as it optimizes land’s production through varied farming, where trees play the central role. Agroforestry systems are characterized by sustainability, high productivity, and socioeconomic adaptability. These outputs are achieved because agroforestry systems are based on natural ecosystems where interactions between different components (such as soil, water, and light) are boosted. Additionally, it can be adapted to farms of different sizes, especially by smallholders in tropical regions where access to other technologies might represent a major cost (Gardi et al. 2014).

Another strategy to prevent land degradation is conservation agriculture which has three main basic rules: (1) zero or minimum tillage, (2) permanent soil cover, and (3) crop rotation (OECD and FAO 2019a, b). Many farmers have shifted to conservation agriculture because it has proven to have great potential in different agroecological zones and farm sizes, especially small production units that confront the lack of manual labor. CA is regarded as a sustainable soil management practice because it combines agricultural production and environmental protection (Gardi et al. 2014; Martínez Gamiño et al. 2019). According to Gardi et al. (2014) the main benefits of CA to the environment are: (a) an increase in soil organic matter, important for soil fertility and health; (b) enhancement of soil structure and conservation of water, by improving soil structure the infiltration of rainfall events increases and this contributes to maintain the ecological flow of water; and (c) higher biodiversity, as plant covers provide shelter for different species.

Precision agriculture is a novel management method that makes use of geolocation, proximal and remote sensing, together with geographic information systems (GIS). The purpose of PA is to understand and calculate variations in topography that can be used for agricultural practices. Some of the benefits of PA include optimum planting density, efficient use of fertilizers, and crop yield prediction and monitoring. Consequently, precision agriculture reduces the impact of agriculture on the environment, increases competitiveness by making efficient use of inputs, and adjusts management practices to plant requirements. In addition to the advantages that PA brings, it provides meaningful data for monitoring and decision making (Gardi et al. 2014).

Lastly, practices aimed at erosion control such as riprap construction, hydroseeding, mulching, willow fencing, terracing, and the use of cover crops have shown significant achievements that result in soil conservation, especially in regions that present favorable conditions for water and wind erosion (Geissert et al. 2017; Prieto and Osorio 2019).

30.5 Importance of Soil Strategies

Soil strategies include every action in the form of research, policy, extension, and education services aimed at the improvement and conservation of soil health in a region. Environmental policies in the LAC region are contrasting. From countries that have already implemented strong measures to decrease the impact of environmental issues, to countries that are starting the look for policies aimed at environmental protection. However, most national agendas are directed towards the regulation of human activities' effect on ecosystems (Gardi et al. 2014).

The United Nations Convention to Combat Desertification has been the traditional framework under which most nations have approached soil degradation. This international agreement provides institutional tools that facilitate cooperation, resource optimization, data generation, and project execution. Nevertheless, LAC countries have just started to integrate soil degradation and climate change topics; therefore, strong frameworks from a political-institutional perspective are needed (Gardi et al. 2014).

Some examples of good policies among the LAC region are Cuba and Uruguay. These countries have detected areas prone to soil degradation that require prevention measures and areas that are already affected by erosion and need to be rehabilitated. Cuba identified soil degradation as the main environmental issue since it affects 76% of their land. Given this situation, in 1993 the government launched the 179 Decree, which established mechanisms to better protect, manage, and conserve Cuban soils. In 2001, the National Program for Soil Improvement and Conservation was developed with the objective of subsidizing farmers so they can manage their soils properly, this policy included the application of organic fertilizers and cover crops, the construction of small dams or drainage levees. This program was coordinated by the Soils Institute of the Ministry of Agriculture, which certificated all their technicians before the policy was implemented. Together with this program, the government has developed more within their Environmental Agenda, such as the National Program to Combat Desertification and Drought as well the National Forestry Program (Gardi et al. 2014).

Uruguay has undergone an agricultural expansion and intensification process due to an increasing international demand. Over the past 15 years, the country has quadrupled its grain production. Of special attention for the government and specialists is the responsible management of soil resources to ensure long-term sustainable production. In that sense, the Uruguayan government declared the Soil and Water Conservation Law in which soil conservation is pointed out as national interest and the role of state agencies in preventing and controlling soil degradation. The regulation involves land use and responsible soil management plans that consider soil type, crop sequence, and management practices. These plans were submitted in 2010 and assessed in 2012 by governmental technicians and private companies, having very positive results (Gardi et al. 2014).

More strategies are needed in Latin America and the Caribbean, an area that constantly faces land use changes, soil degradation and contamination due to human activities. These strategies should involve farmers and stakeholders in the assessment, planning, execution, and monitoring of actions aimed at improvement and conservation of soil resources.

30.6 Future of Soil Science Research and Education in LAC

Soil science research and education in the region has mainly focused on agricultural related topics. However, with great upcoming challenges upcoming such as climate change, a growing population, and the impact of human activities, the study of soil systems will become more complex. We believe that soil science in LAC has still many areas to do research on, for instance: (1) the development of inexpensive monitoring of soil resources with the aid of proximal and remote sensors, (2) tracking and understanding land use change impact on soil and water resources, (3) the role of diverse microbial communities on the overall ecosystem, (4) novel soil conservation techniques, (5) creation of new sustainable management practices, (6) assessments of the impact of climate change in the multiple ecosystems in the region, particularly in arid zones, (7) soil organic carbon dynamics related to agricultural management practices especially in the tropics, (8) constant update of soil databases together with stronger national sampling campaigns, (9) soil carbon sequestration potential in the different regions of LAC.

Moreover, these new research opportunities must be accompanied with strong policies, training and education of new soil scientists, agreements with the private sector, and international cooperation. Soils will play a determining role in the resolution of many issues such as food and water security, poverty, and creation or new sources of energy.

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The Frontiers in Soil Science Research: An African Perspective

31

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Abstract

The beginning of soil resource inventories, which was the dominant soil research in many African countries, is dated back in the early twentieth century; some countries started with systematic soil survey, some with reconnaissance studies, and others produced general information with local soil observation. The 1970s FAO-UNESCO volume VI was the first ever official map of African soils with the scale of 1:5 M. This chapter focused on the glimpse of advancements and collective achievements of soil research in Africa and highlighted existing challenges and opportunities to suggest their implications on the future of soil research advancement in the continent. A systematic literature survey of the web of science core collection, expert knowledge and compilation of Africa centric soil research were conducted, and development reports and books on achievements, challenges, and opportunities published by different national, regional, and international institutions including the Consultative Group on International Agricultural Research (CGAIR) and the Food and Agriculture Organization of the United Nations (FAO) were reviewed. Results showed that most of the past 100 years soil research in Africa were supported and promoted by funding from international and multinational donor organization. However, several soil researches done by local universities and research institutions were not accessible through the global database, which has been one of the biggest challenges for knowledge sharing. Key biophysical and systemic challenges in African soil research included: land degradation, soil nutrient imbalances,

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research priority mismatch, and helicopter researching. The availability of 30 m resolution continental digital soil map is marked as a key achievement to design sustainable soil heath interventions in the future. Finally, six key issues are put forward, as a well thought out option to advance soil research in Africa in the remainder of the twenty-first century, these are: (1) revising and integrating soil research in academia, (2) establishing a robust knowledge and data management system, (3) standardization of methods, (4) increasing crop response research data, (5) validating predictive soil map outputs, and (6) calling for continental alliance for soil interventions.

Keywords

Africa · Soil · Twenty-first century

31.1 Introduction

The soil beneath our feet serves as springboard both to hold-tight the balance in nature (soil is a carbon pool) and increase agricultural productivity. Knowing soil statuses are key in terms of identifying the gaps to conserve the resource and design intervention strategies to sustainably intensify agriculture. Conserving this non-renewable resource requires the involvement of all actors: researchers, development actors, policy markets, private sector, and farmers; the global citizen in a collective term.

The beginning of soil resource inventories in Africa is marked back in the early twentieth century; some countries started with systematic soil survey, some with reconnaissance studies, and others produced general information with local soil observation (Young 2017). Available records from historical perspectives for other countries like Ethiopia indicated that maps showing soils of Ethiopia date back to 1920s (Esayas and Debele 2006). Soil research in Africa, especially in sub-Saharan African countries was dominated by soil survey in many countries, especially the Britain's colonial countries in Africa like Malawi, Zambia, Uganda, Ghana, Gambia and Sudan during the 1950s and 1960s (Young 2017). With the intent to conserve soil resources and grow more for the increased number of the populations on these countries, land resource survey was extensively conducted after the second world war (Webster 2018). However, there were no consistent methods of soil inventory and research in most of the African countries. The 1970s FAO-UNESCO volume VI were the first ever official map of African soils with the scale of 1:5 M (FAO/UNESCO 1977). Since then, several local and coordinated studies in partnership with different institutions globally have been undertaken. The continental wide initiative commenced in 2009—the African Soil Information Service (AfSIS) was one of the remarkable works in the era of digital soil mapping (DSM) that laid foundation for the current innovative solutions for decision agriculture (ISDA) in terms of innovations and data compilations (Hengl et al. 2017, 2020). The objective of this chapter was to focus on the glimpse of advancements and collective achievements of soil research in Africa, and highlight existing challenges and opportunities to suggest their implications on the future of soil research advancement in Africa.

31.2 Methodology

A systematic literature survey, expert knowledge and compilation of Africa centric soil research were conducted, and development reports and books on achievements, challenges and opportunities published by different national, regional and international institutions including the Consultative Group on International Agricultural Research (CGAIR) and the Food and Agriculture Organization of the United Nations (FAO). A key word 'soil research in Africa' was used to access published articles from 1900 to 2020 in the web of science core collection. These publications and other supporting reports were synthesized to present the achievements in soil research in Africa to date, and existing challenges and opportunities to suggest future interventions to advance soil research in the continent. This published resource in the web of science might not have covered all available scientific contributions since most of research outputs done by graduate students in local universities and research institutes are not indexed in the web of science core collection. This review discussed key knowledge gaps in the soil science, barriers in term of institutional capacity, financial and human resources to amplify the need for restoration of degraded lands in Africa, and existing soil information.

31.3 Results and Discussion

In the survey for literature conducted in November and December 2020, a total of 254 records were obtained, and the proportion of the total publications on soil science were 79% articles, 22% proceeding papers, 8% reviews and a book chapter that fall in the categories of agronomy (23.6%), environmental sciences (17%), plant sciences (15%), water resources (9%), chemical analytical (9%), geosciences multi-discipline (7%), and other related disciplines in descending order of manuscript counts. This explicitly showed that soil science is an integral part of other related field of sciences, and research in soils were not considered a stand-alone, so it was intertwined with different field of studies and sub-disciplines. In the past two decades, a large number of papers were published in 2007 followed by 2003 and 2019, respectively (Fig. 31.1). Only most relevant and related publications were reviewed in this chapter. The majority of these studies were promoted and enhanced by the CGIAR and Wageningen University with a collectively great deal of funding from international and multinational donor organization such as the Government of Japan, European Union, USAID, and Australian Aid. One remarkable local funding that supported several soils research was the National Research foundation of South Africa. At least based on this web of science core collection, most of the past 100 years of soil research in Africa was promoted by external funding sources,

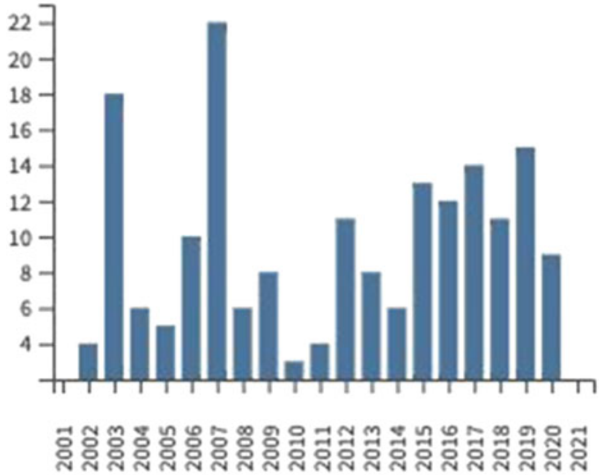

Fig. 31.1 The number of soil research papers published between 2001 and 2020

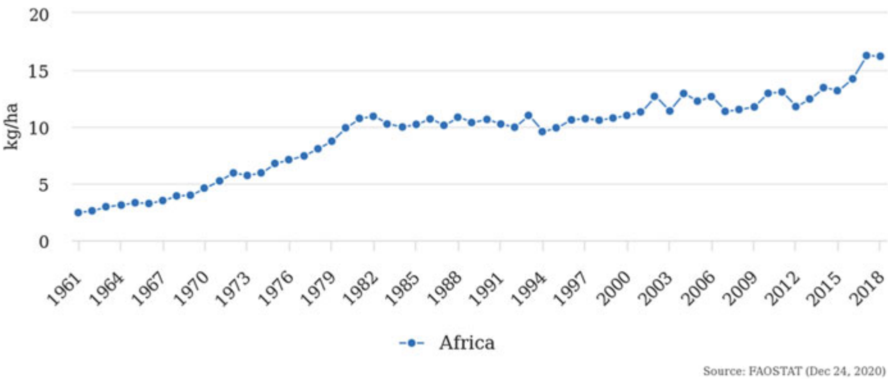

Fig. 31.2 Nitrogen N (total) use per area of cropland from 1961 to 2018 (FAO 2020)

however, majority of research communications produced by local research institutes and graduate students at local universities are not indexed in global database. For example, several soil researches done by local universities and research institutions in Ethiopia are published by Ethiopian Journal of Natural Resources (EJNR), which was not accessible through the global database and made the articles hard to find.

31.3.1 What Do We Know and What We Do Not?

31.3.1.1 Land Degradation as a Challenge

Land degradation in all its forms, e.g., nutrient depletion, erosion, diminished soil biodiversity, etc., have been the major challenge in Africa (Bennett et al. 2012;

Dahlberg 2000; Dregne 2002; Mchunu and Chaplot 2012; Weinzierl et al. 2016). The degraded lands resulted in quantifiable negative nutrient balances from plot to the continent and the causes have been complex, among others, poor practice of returning crop residues to fields, deforestation, soil acidity, and soil salinity are the major ones. In some parts of Africa, water erosion alone removes more than 100 kg of Nitrogen (N) from a hectare of land every year on average (Vaje et al. 1999), which was ten times more than the average annual application rate of N on croplands in Africa (Fig. 31.2), and these problems are much aggravated due to the pressure from ever increasing population.

Healthy soils play a pivotal role in achieving several social and ecological benefits and soil is the core to binding many of the sustainable development goals (SDGs) in one or another way. This is connected to soil quality, which is the measure of soil functions in a given ecosystem in terms of maintaining and improving soil while ensuring improve food security and reduce poverty. It is nontrivial to appreciate the role organic carbon contents of soils play in improving soil health since it is key to improve the ability of soil to retain water, remain fertile and good structure. The total carbon stock for the top 1 m of African soil is estimated to be 155 Gt (Lal 2017), apparently drastic decline on soil organic carbon contents are reported at different geographies in Africa (Nandwa 2001; Swanepoel et al. 2016). Reports showed that conservation agriculture and integrated soil fertility management (ISFM) positively impacted infiltration, reduced run-off, and soil erosion by more than 44, 30, and 33%, respectively (Kihara et al. 2020), and ISFM alone is reported to increase crop yields significantly (Agegnehu and Amede 2017). In addition to land management practices in different farming systems, the content of organic carbon in African soils was much affected by factors like agroecology and soil types (Njeru et al. 2017; Yost and Hartemink 2019). However, the primary focus of soil research in Africa over the past years was looking at the lens of crop production and productivity, but a few researches reported the nutrient use efficiency for specific crop types such as millet and water use efficiency in the western part of Africa (Christianson and Vlek 1991; Fathololoumi et al. 2020; Pala and Oweis 2003; Sarr et al. 2008).

31.3.1.2 Soil Nutrient Mining and Imbalances

Traditional farming in Africa is far from sustainability and the amount of nutrients annually removed from agricultural fields reach 200 kg/ha (Vaje et al. 1999), which was way above the amount of nutrients applied through inorganic and organic sources, and generally characterized as low rate of nutrient application (Fig. 31.2).

The key issue in soil nutrient mining has been linked to limited knowledge on nutrient requirement for different crops and imbalanced nutrient applications due to micronutrient deficiencies (Phiri et al. 2019). This led to 'blind' input recommendations that often have led to uncertainties in agronomic gain targets. For instance, the adoption of inorganic fertilizers in Ethiopia was limited to only two fertilizer types Urea and DAP, to supplement N and P nutrients only, for more than five decades regardless of the requirement of crops and the soil statuses. This is directly linked to the lack of crop response data for soil health improvement

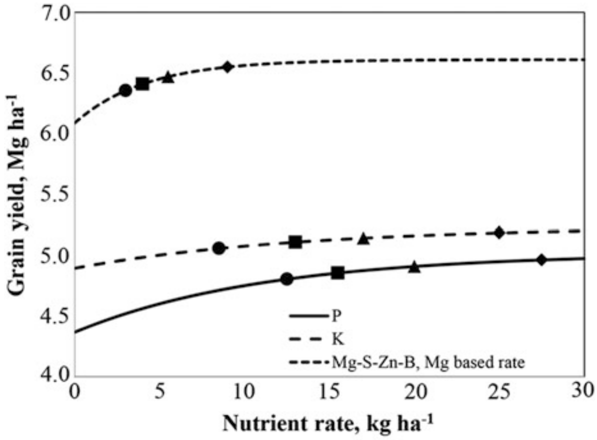

Fig. 31.3 Response of wheat to P, K, secondary and micronutrients in Rwanda from Cyamweshi et al. (2018) (The economically optimal rates for maximizing profit per hectare are indicated for the cost per kg of nutrient use equal to the value of 4 (filled diamond), 7 (filled triangle), 10 (filled square) and 13 (filled circle) kg of wheat grain. The response to Mg, S, Zn and B was based on the Mg application rate and the nutrient rate ratio was 1:1.5:0.25:0.05, respectively (Cyamweshi et al. 2018))

interventions. Soil fertility assessment and fertilizers recommendation are mainly based on soil test results and blanket application of fertilizer applications have been the common practices. There is a need to tailor fertilizer recommendations for different crops at plot level and this requires a multi-year geo-referenced crop-nutrient response data since promising results were reported from correlating such data with biophysical and environmental data. For example, nutrient response function model developed for maize showed scalability to other maize growing area that had sufficient crop response data in sub-Saharan African countries. In their study in Eastern Africa, Cyamweshi et al. (2018) reported the importance of investigating and develop yield response function for different types of nutrients is key to formulate economically optimal recommendation rates for resource poor farmers (Fig. 31.3).

31.3.2 Key Knowledge Gaps and Research Priorities

A recent article on nature (Ending hunger 2020) pointed out that there were priority mismatch between international agricultural research funding and smallholder farmers' need. Farmers assumption on the qualitative assessment of their soils and laboratory analysis do not agree in some cases (Buthelezi-Dube et al. 2020). This mismatch in research priorities directly affect the adoption of technologies by farmers that are meant to be the forefront beneficiaries. On the other hand, adoption rate of technologies on sustainability of agricultural soil resources, e.g., soil carbon sequestration technologies, have shown a significant increase over the past two decades. Even though there were high adoption potential, lack of inputs and machineries for practices like conservation agriculture affected the rate of adoption, and providing trainings to farmers in order to close skill gaps on specific technologies and changing perceptions were identified as critical to enhance adoption rate of technologies (Enyong et al. 1999; Ndah et al. 2015; Ng'ang'a et al. 2020). It is also important to appreciate farmers indigenous knowledge, local tradition, and matching technological options that are tailored to the socioeconomical context in terms of soil quality, soil and water conservation measures to ensure a successful adoption of technologies (Critchley et al. 1994; Kuria et al. 2019; Sterk and Haigis 1998).

31.3.3 Systemic Barriers

During a virtual special symposium on 'Translating visionary science for excellence in African Agronomy' at ASA-CSSA-SSSA 2020 conference, scientists argued that international scientists and donors should start to take national agricultural researchers and their institutes in Africa seriously, and they firmly voted that international scientists have had the chance and it did not work out very well. Thus, they recommended that it is the time to shift the responsibility and the resources to the people on the ground. In addition, it has been reported that helicopter researching is negatively impacting successes in soil research in Africa (van Groenigen and Stoof 2020; Haile 2020).

31.3.4 What Soil Information Exist

Studies on the spatial variabilities of soil properties and investigating different algorithms to create best validated DSM products are being largely used (Batjes 2008; Flynn et al. 2019, 2020a, b; Hovhannissian et al. 2019; Nocita et al. 2011; van Zijl 2019; van Zijl et al. 2019; Voortman et al. 2004; Voortman and Brouwer 2003). These efforts are complemented by the continental scale soil properties and soil fertility status maps (Hengl et al. 2017, 2020). Integrating and correlating soil information versus crop-responses data to refine agronomic approaches require further research on the continental scale digital soil maps using different sets of data for site specific soil health improvement interventions and management recommendations.

The harmonized soil map of Africa that has shown the distribution of major soil types defined using reference Soil Groups of the World Reference base (WRB) is the only continental wide soil type map available at 1:3 M scale (Dewitte et al. 2013). This map has too course resolution and only major soil mapping units (SMUs) were included, and it requires additional data for country specific integration of different environmental spatio-temporal layers and ground level data to analyse and formulate specific decision making (Fig. 31.4). Investigating the differences between

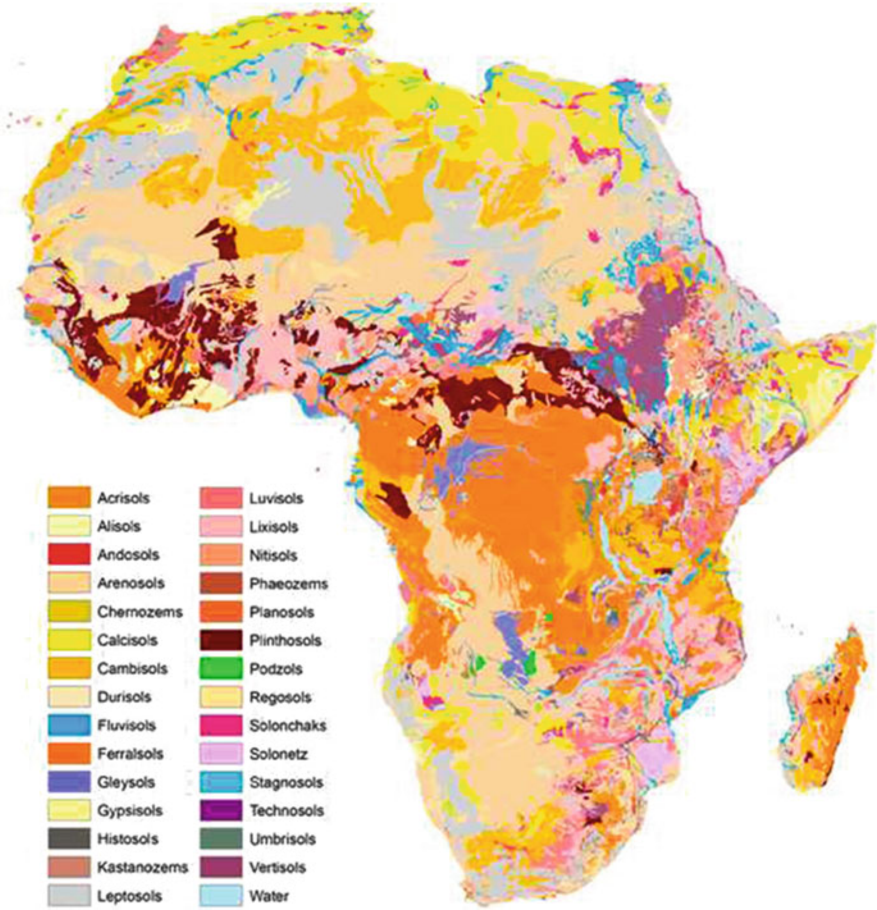

Fig. 31.4 Harmonized soil map at the continental scale from Dewitte et al. (2013)

categorical and continues mapping on this version of map with additional dataset is worth to investigate to address the need for updated soil type of Africa.

The Hengl et al. (2020) continental scale soil properties and nutrients maps (iSDASoil) is a direct contribution towards knowing the African soils—precisely speaking, with a fine resolution of 30 m. This detailed map is able to show more than ten distinct variabilities (in a very heterogeneous field scenario) in a hectare of smallholder farmer's field, which makes it one of the greatest breakthroughs that can support the designing of more tailored soil management strategies. In the previous version 250 m resolution digital soil nutrient map of the SSA (Hengl et al. 2017), fertility capability classifications, and agronomy information were not integrated with the physicochemical characteristics of the soils in Africa, which will definitely help all actors to do the right things right.

By the same token, the effort and investment made to establish soil information systems in Africa is one of the major achievements that had laid a foundation for countries that took the initiative to establish their national soil information system, e.g., Tanzania, Ghana, Nigeria, Rwanda, and Ethiopia. The Ethiopian Soil Information System (EthioSIS), for example, has targeted digital soil mapping methods soil test based tailored fertilizer recommendation at sub-district (kebele) level using extensive topsoil samples gathered from croplands for smallholder farmers (ATA 2014).

31.4 Implications/Conclusions

The future of soil information service delivery should immerse into income generating business in public private partnership. This potentially drives innovative ways of making soil science and linking with the sustainable development. For example, the rapid and non-destructive spectral analysis method can connect millions of the African smallholder farmers with the technology.

Ensuring a successfully advanced soil research in Africa in the remainder of the twenty-first century, as an integral part of a sustainable improvement to African agriculture, summon well thought out solutions for the following six key issues:

1. Revise and integrate soil research in academia.
   The number of African soil scientists are small and majority of these scientists work in education sector and national research institution, and only 4% of the African soil scientists are in the international research institutions (Rozanov and Wiese 2018). The scientists working in local institutions, which accounts for 39% of the total soil scientist human capital pool in Africa, has to go far to designing country specific and continental consortia to support soil research through educating, supervising, and mentoring the future soil scientists. The proportions of the field of specialization and gender balance have not been showing healthy trend since it has been dominated by male soil scientists (Rozanov and Wiese 2018).
2. Establish a robust knowledge and data management system.
   Accessing local research outputs that are not indexed in the global databases is one of the largest barriers in knowledge sharing in soil research and beyond in Africa. Indexing research work in global databases is key to ensure robust knowledge management system.
3. Standardization of methods in soil data collection, analysis and reporting.
   Strengthening the African Soil Laboratory Network (AfriLAb) under the global soil laboratory network (FAO 2019), which aimed at addressing the issue of inconsistencies of soil data collection by laboratories could be an avenue to harmonize and standardize soil data collection and the subsequent analysis and reporting.
4. More crop response research to improve the granularity of recommendations on soil health improvement for agronomic gain is pertinent.

5. Validation of predictive soil maps.
   In this era of digital soil mapping, computer assisted creation of spatial and temporal information of soil properties is being well assimilating in the science; several maps are being produced locally and at continental scale with fine resolutions, however, high resolution does not always mean accurate information (Costa et al. 2018). Validation of such DSM products depend on model based and product level validations, which are very crucial to increase the confidence level of decision makers and end users to make sure success rate on adoption of the technologies is positive. A future research question suggested by (Peter 2018) provides an opportunity to explore the synergies between different soil resources improvement and management methods to support policy decisions.
6. Continental alliance for soil interventions.
   Strong partnership in soil research and beyond is critical, and collaborations between institutions must go beyond ill-defined interests of securing funds. At the same time, national institutions should be given the priorities to do the research while ensuring required capacity building and minimizing helicopter researching is (van Groenigen and Stoof 2020; Haile 2020). Unlocking such systemic challenges help to upgrade existing databases, on the other hand, researching on different approaches will improve the scientific methods. One key aspect is establishing strong collaborations with local research and development organizations and international institutions for joint problem identification and well-aligned research.

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Improvement of Soil Quality by Solid Waste Recycling: A Global Perspective

32

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Abstract

In India, with increasing urbanization, industrialization and agricultural activity, a large amount of byproducts are produced as waste. The management or recycling of the waste material thus generated is a major challenge in our country owing to an inadequate infrastructure for their collection, transport, treatment and disposal. Moreover, less than 20% of the total wastes are treated every year and the untreated portion makes its way into natural resources like rivers, lakes and wetlands. As a result, our surrounding environment gets polluted consequently leading to the deterioration of human and animal health. Application of such waste material to the soil for improving soil fertility and crop productivity is a sustainable alternative which has received increased global attention though recently. Hence, recycling of waste into potential fertilizer products can curtail the dependency on inorganic fertilizers, thereby reducing the problems associated with the treatment as well as disposal of huge amount of wastes. The utilization of the agricultural and industrial wastes or municipal solid wastes after composting, vermicomposting or anaerobic digestion as soil amendments can provide soil nutrients, enhance soil organic matter and improve soil structure ultimately leading to an increased nutrient uptake by the plants. In this chapter we will be

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discussing about the different types of organic and inorganic waste materials (WM) which are produced from industrial, household and agricultural activities, along with the traditional and recent approaches of their management to improve soil quality and crop productivity. This chapter also includes a discussion on how such application of solid waste changes the soil physical, chemical and biological properties. Different schemes and policies for waste management in India have also been highlighted in this chapter along with the future management prospects of SW to improve soil quality in a sustainable manner.

Keywords

Recycling · Solid waste management · Soil quality · Sustainability · Urbanization

32.1 Introduction

Solid waste (SW) is the byproduct of socio-economic activity in our modernized society. The definition of solid waste therefore varies from one country to another. According to the Resource Conservation and Recovery Act (RCRA), 1976, America, the term 'solid waste' refers to any garbage, discarded material or sludge generated from industries, agricultural operations and human activities (USEPA 2018). They did not confine the definition of solid waste to physically solid state materials but also include many liquid, semi-solid or contained gaseous material. Basically, any unwanted or useless solid, semi-solid or liquid materials produced from community activities in household, agriculture, industries and commercial areas are considered as solid waste (IWP 2020). The quantity and variety of those solid wastes are increasing day by day with growing population, industrialization and also with rise in standard of living more prominent in developing countries (Minghua et al. 2009). Therefore, in developing countries management of solid waste is a major challenge due to the lack of infrastructure for their safe disposal and limited knowledge about their characteristics which ultimately affects the entire ecosystem.

32.1.1 Adverse Impact of Improper Solid Waste Management in Ecosystem

The improper management of SW is very detrimental for human and animal health. It adversely affects the aquatic ecosystems and water bodies, causes soil contamination, air and ground water pollution with other serious environmental impacts such as depletion of ozone layer, emission of greenhouse gases (GHGs), etc., which eventually enhances the overall impact of climate change (Ayilara et al. 2020). The large proportion of SW produced due to industrial, agricultural and other anthropogenic activities are very diverse in nature and contain many essential nutrients, especially the residential waste which is organic in nature and contains huge amount of easily degradable organic carbon (C), nitrogen (N) and phosphorus (P), etc. If those organic wastes cannot be handled properly it can cause eutrophication with enormous formation of algal bloom and other disruption in ecosystems (Bekchanov and Mirzabaev 2018). Those harmful algal bloom sometimes produce detrimental cyanotoxins which are also injurious for human and animal health (Merel et al. 2013). During rainy season, the water soluble nutrients from wastes can make their way to ground water and subsequently enter into the food chain, thus causing extreme health disorders like Parkinson's disease, cancer, birth defects, Alzheimer's disease and reproductive problems in humans (Kim et al. 2017). It has also been found that due to improper treatment and disposal of SW, around 1.6 billion tonnes of CO_2 equivalent GHGs were emitted in the year 2016 that is likely to increase to 2.38 billion tonnes by 2050 (Kaza et al. 2018). The huge amount of farm waste, crop residues (CR), etc. which are generated due to agricultural activities are rich sources of organic C and other essential nutrients. Reportedly in India, approximately 92 million tonnes of CR is burnt every year, which is greater than the entire waste generated in Bangladesh, Indonesia and Myanmar (NPMCR 2019; Jeff et al. 2017). The illegal burning of CR and collected SW (a) emits GHGs (CO2, CH4, CO, NH3, NOX, SOX) that contribute to global warming, (b) increases the level of other air pollutants (non-methane hydrocarbon, volatile and semi-volatile organic compounds) and particulate matter along with hazardous smog which are detrimental for human health, (c) leads to loss of essential nutrients from soil, thus, reduce soil fertility and (d) causes biodiversity loss from agricultural land (Jethva et al. 2019; Bhuvaneshwari et al. 2019). Repeated application of untreated SW in agricultural fields is detrimental for beneficial soil microbes and can also cause many soil borne diseases (Ramírez et al. 2019) and eventually deteriorate soil health and quality.

32.1.2 Importance of Solid Waste for Improving Soil Quality

With consistent industrialization and modernization of agriculture along with the increasing concerns for environmental protection, the main focus of modern society has shifted to agricultural sustainability. As maintaining soil quality is the prime concept of agricultural sustainability, the impact of agricultural management practices on soil quality needs to be given due importance. The term 'soil quality' is defined as the inherent capacity of soil to function within an ecosystem boundaries for maintaining an optimum productivity of plant and animal while concurrently improving surrounding environment for supporting human health and their habitation (Karlen et al. 1997; Schjonning et al. 2004; USDA NRCS 2017). The quality of soil is greatly affected by different physical, chemical and biological soil properties and any changes in those properties ultimately affect the soil quality. The main anthropogenic reasons for soil quality deterioration in agriculture are intensive cultivation with high analysis fertilizers, imbalanced fertilization without secondary and micronutrient addition, less application of organics along with inorganic fertilizers, lack of crop rotation and legume inclusion, etc. (Basak and Mandal 2019) which deplete the soil natural resources. As it has already been discussed that most of the organic SW is a good source of easily available nutrients, thereby having the potential to be used as organic fertilizer source or amendments for improving crop productivity and soil quality, after proper treatment. Among the inorganic SW, waste mica, fly ash, different fertilizer byproducts, etc. also act as good source of nutrients for plant growth and development. Therefore, the application of SW in the form of compost, manure, fertilizer and as other soil amendments not only eradicates the problem of waste handling in developing nations but also improves the soil condition for better crop growth in a sustainable manner.

Keeping in view the importance of SW management and improvement of soil quality, the purpose of this book chapter is to present an elaborate discussion about the different types of organic and inorganic SW materials generated in India as well as in world, along with the traditional and recent approaches for their management to improve soil quality and crop productivity. An account of the policies, schemes and future prospects of research for solid waste management in India has also been presented in this chapter.

32.2 Generation of Solid Waste and Its Recycling in India to Global Context

With the rapid growth of population and urbanization the generation of waste also increases and it was found that every year 7 to 9 billion tonnes of waste are generated worldwide (Wilson and Velis 2015). Municipal solid waste (MSW) accounted 2.01 billion tonnes of the total waste in the year 2016 and was expected to increase to 3.40 billion tonnes in the year 2050 (The World Bank 2019). The overall waste generation is 0.11–4.54 kg per person per day which is likely to increase by 19% in the developed and high income countries by 2050 (Kaza et al. 2018). The quantity of waste generated in the fastest developing regions like Sub-Saharan Africa, South Asia and the Middle East and North Africa will be amplified from two to three times in 2050. Out of total waste generated worldwide, food and green waste accounted only 32% in developed nations, whereas in developing and under developed countries those values were 53 and 57%, respectively (Kaza et al. 2018).

In India, highest amount of waste is generated every year all over the world. India generates about 960 million tonnes (MT) of SW per year as the byproducts from domestic household, mining, industry and agriculture (Pappu et al. 2007). Approximately, 290 MT of inorganic waste was generated from industry per year (Pappu et al. 2007). According to 2016 estimate, the generation of MSW was 277 MT per year which accounted around 80 and 13% of waste generated across the Asia and World, respectively (TOI 2020). Among the different states national capital Delhi produced maximum amount of waste (30.6 lakh tonnes) followed by Mumbai and Chennai (TOI 2020). The MSW accounted 50% waste generated in India. Apart from MSW, agricultural sector of India generated on an average 620 Mt. of crop residue every year (NITI Aayog annual report 2014-15). After consumption of CR as fuel, fodder and other industrial purpose 140 Mt. is in surplus and out of which 65% residue has been burned every year (NPCRM 2019).

32.3 Types of Solid Wastes Suitable for Soil Quality Improvement

The Resource Conservation and Recovery Act (RCRA) categorizes SW into: hazardous and non-hazardous waste. Based on sources, the non-hazardous solid wastes are further divided into (a) municipal solid waste (MSW) that are mainly from household as well as commercial wastes; (b) agricultural waste; (c) industrial waste and (d) construction and demolition waste as illustrated in Fig. 32.1. In this chapter main emphasis is given to the non-hazardous SW which can be applied directly or indirectly (in the form of compost or manure or after proper treatment) to agricultural fields for improvement of soil quality.

1. Municipal solid waste (MSW): These consist of mainly organic waste (food and garden) (the organic waste), paper waste, textiles, plastics, metals and glass, etc. from residential, commercial, institutional and industrial sources. The composition of MSW as well as their generation rate varies among different cities with varying levels of socio-economic development along with the seasons variability. Central Pollution Control Board (CPCB 2016) reported that 62 MT of MSW was generated in India in 2015 which was equivalent to 169,864 t/day or 450 g/capita/day (urban area). They also forecasted that it will be increased to 300 MT per year (945 g per capita) by the year 2047. Further, it is also reported that 40–60% of the total part of generated MSW can be composted, 30–50% remains as inert waste and 10–30% can be recycled (Planning Commission Report 2014). The C, N, P and potassium (K) content of MSW varied from 17 to 41, 0.50 to 1.06, 0.61 to 0.93 and 0.42 to 0.76%, respectively, whereas the C/N ratio varied from 26 to 45 (Vyas 2011). Therefore, after proper treatment, MSW can be used as nutrient source to soil and have the potential to improve soil fertility. Available treatment options for MSW are composting, landfilling, incineration, remoulding, etc. Among these, different compost from composting of biodegradable portion of MSW (e.g., agro-industrial, rice bran, wheat bran, corn cob.) are important from soil quality point of view.
2. Agricultural waste: Agricultural wastes generally include crop residues from the farm and other residues from fruits, vegetables, dairy poultry, meat and products (raw agricultural products). Therefore, their composition depends on the existing ecosystem and type of agricultural activities are being done. They are also otherwise called as agro-waste which includes crop waste, animal waste, food waste and toxic agricultural waste (pesticides, insecticides, herbicides, etc.). Broadly, agricultural waste can be divided into two types:
   (a) Farm waste: Generally, it includes crop residue and plant biomass, animal dung and urine, poultry excreta and fish waste. All these wastes are directly linked with the farm activities. Among all the farm wastes, crop residues are also considered to be 'potential black gold'—a natural and valuable resource

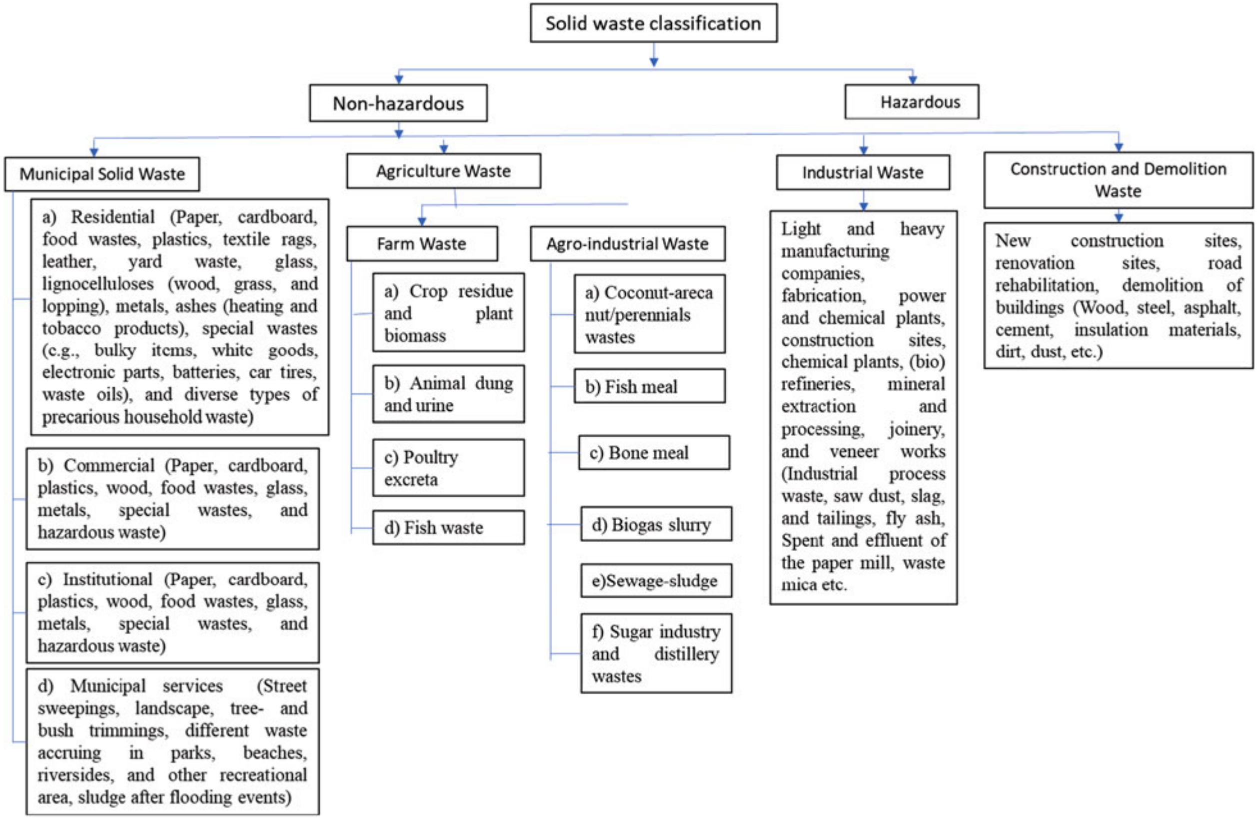

Fig. 32.1 Classification of solid waste

Table 32.1 Nutrient potential of different crop residues in India

Crop	N (%)	P_2O_5 (%)	K_2O (%)
Rice	0.61	0.18	1.38
Wheat	0.48	0.16	1.18
Pulses	1.29	0.36	1.64
Oilseeds	0.80	0.21	0.93
Sugarcane	0.40	0.18	1.28

Source: adapted from Tandon (1997)

Table 32.2 Content of major nutrients in some agro-industrial wastes (% on oven dry basis)

Waste product	N	P_2O_5	K_2O
Bone mea	3	20	–
Fish meal	7	6	1
Safflower cake	8	2	2
Groundnut cake	7	1.5	1.5
Castor cake	5.5	2	1.5

Source: adapted from Biswas and Mukherjee (2003)

(Reicosky and Wilts 2005) as they supply significant quantities of nutrients for crop production (Table 32.1). Among the crops, cereals comprise 58% of the total residue (620 MT) generated in India (NITI Aayog annual report 2014-15) and Uttar Pradesh is the leading state in residue generation. Another form of farm waste available in India is animal waste (from cow, buffalo, goat, sheep, poultry, etc.). According to 20th Livestock census 2019 report, the population of animal and livestock in India is about 535 million and excreta generated from them is 407 Mt. and highest percentage is contributed by cattle. Two-thirds of this animal waste are used as fuel cake and the remaining one-third for manure production. Therefore, animal manures can be used as plant nutrient sources to improve soil health that would also add to its economic value, though nutrient concentrations in the manures are highly variable.

(b) Agro-industrial waste: A huge amount of wastes are generated from agricultural-based industries every year. These are comprised of coconut-areca nut/perennials wastes, fish meal, bone meal, biogas slurry, sewage sludge and sugar industry and distillery wastes. Most of these untreated wastes cause environmental pollution which are detrimental to human and animal health. Therefore, sustainable management of these waste is the need of the hour by converting it into cleaner and greener renewable bioenergy resources (Okonko et al. 2009). Besides, having high nutritional prospective (Table 32.2), they are also considered for valorization to produce agro-industrial byproducts (Graminha et al. 2008).

(c) Industrial waste: Rapid industrialization has led to the production of liquid and solid waste. The non-hazardous industrial wastes are saw dust, slag, tailings, fly ash, spent and effluent of the paper mill, waste mica, etc. which are produced from a wide range of industrial processes like various manufacturing companies, fabrication industry, power and chemical plants, (bio)refineries, mineral extraction and processing industry, joinery, veneer working plants, etc. Fly ash, a byproduct of power generation plants, is also considered as solid waste (Ram and Masto 2014). Besides, several other sources of SW are basic metals, sewage and scrap metals, wood products, glass, ceramics, leather, rubber, plastics, waste from food processing, oils, waste from tobacco industry, paper, waste from scientific research, transportation apparatus, dredging, etc. Terms like biosolid and sewage sludge are often used inter-changeably. Biosolids are nutrient-rich organic materials derived from treated sewage sludge. Processed biosolids after proper treatment can be used as soil amendments. Huge quantities of industrial wastes, equivalent to 1900 Mt per year are generated in the Asian region (including China, Japan, Republic of Korea, Hong Kong, Singapore and others in Asian region) (UNESCAP 2000) and are still increasing in alarming rate. Therefore, cleaner waste management technologies for waste minimization are considered to be adapted as early as possible.

(d) Construction and demolition waste: These include debris from the different construction activities, renovation (make over) sites and demolition of old structures (buildings, bridges, roads, etc.). They are generally bulky and heavy in nature, for example, land clearing debris asphalt, concrete, wood, concrete masonry units, metals, carpet, cardboard glass, gypsum wall board, insulation, etc. Among these, only a small part of the wastes would be used for soil quality improvement only after proper treatment.

32.4 Methods of Solid Waste Management in India

Waste management is the process of managing waste from production to its final deposition. In country like India presently urban areas alone generate around 62 million tonnes (MT) of waste, on yearly basis. It is estimated that it may reach up to 165 MT by 2030. In that 43 MT of municipal solid waste is collected yearly but 75% of it simply dumped in landfill sites, only less than 25% is treated. The untreated waste which is left as such has serious impact on environment so management of waste has become a major challenge these days. It is very much important to adopt comprehensive approach in each stage of management like generation, collection, transportation, processing and final deposition. Waste management is a series of stages linked, it begins with the generation of waste till it is treated and disposed off (Fig. 32.2). Solid Waste Management Rules 2016 is applicable to municipal areas, urban agglomerations, census towns, notified industrial townships, etc. and encourages the compost utilization, waste to energy strategies and reconsideration of landfills site capacity and locations in the cities.

Solid waste collection in India is not very planned in every urban or rural areas. India has only 70% waste collection efficiency due to improperly designed, placed and maintained waste bins. Collection is preliminary step in which waste is transferred from the point of production to the place of treatment or landfill sites. Almost half of the solid waste is being collected manually and around 70% is transported by

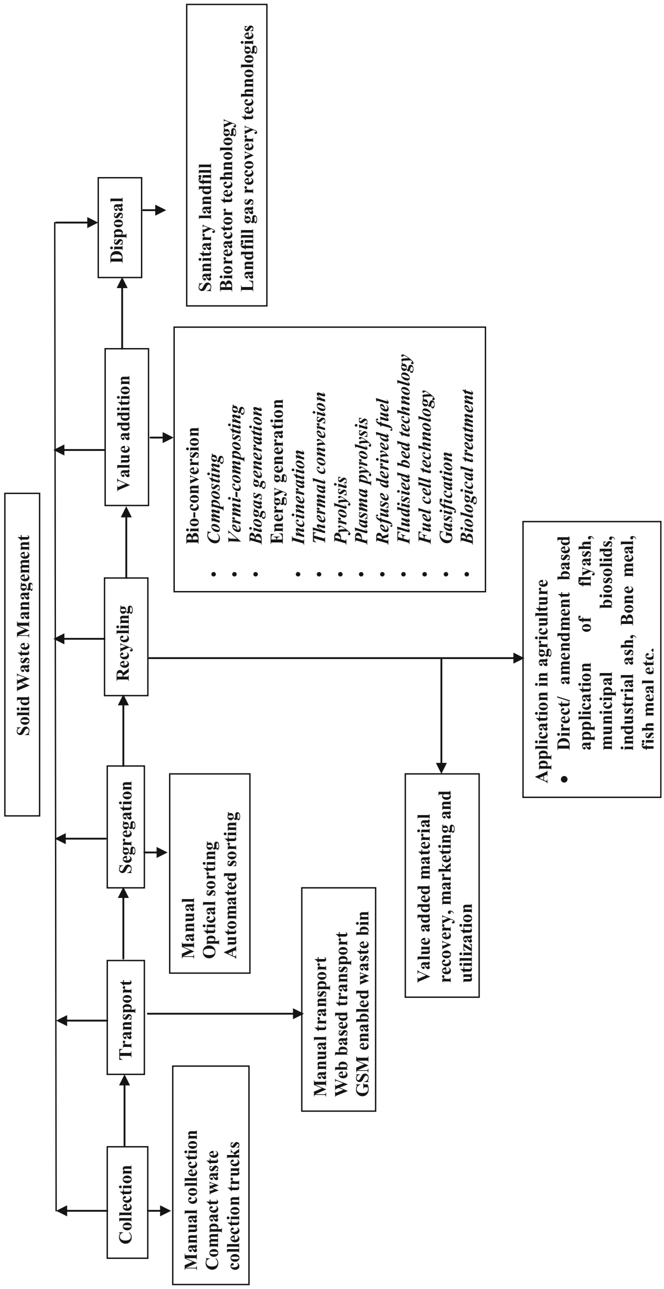

Fig. 32.2 Series of stages for solid waste management with comprehensive approach

Table 32.3 Direct application and value addition of different types of solid waste

Type of waste	Source of wastes	Treatment procedure	Final product (applied to soil)
Organic agro-waste	Agriculture and agro produce based industries	Composting, vermicomposting, anaerobic digestion, thermal treatment	Compost, vermicompost, biogas plant slurry, biochar
Inorganic industrial wastes	Thermal power plants and steel industries, construction site waste	Direct application	Fly ash, bottom ash, steel slag
Mineral inorganic waste	Coal mining waste, metallurgical waste, slaughter-house waste	Chemical treatment, pulverization	Soil additives, bone meal
Non-hazardous inorganic waste	Glass, lime, fertilizer, glass, ceramic and brick kiln waste	Pulverization	Waste mica, gypsum
Hazardous waste	Metallurgical, tannery and galvanizing industrial waste	Chelation to remove heavy metal	Inorganic complex

trucks. Depending on the hazardous or non-hazardous or quantity of waste produced, there are various means for transportation for waste like trucks, railways, ships and other vehicles. The simply biodegradable waste which can be used for composting purpose are considered as wet waste and the nonbiodegradable and recycled waste like plastic, glass, metals etc. are considered as dry waste. Recycling is the process where waste materials collected and transformed into new things that have some utility. It is considered as an excellent strategy for controlling waste based pollution problems, exploitation of natural resources and reduces need for landfill sites. Several materials from especially like aluminium containers, paper, plastic, iron and glass are recycled to produce valuable products like video tape, plastic bottles, polyester, fibre carpets, decorative items, etc. Waste materials can be used again by adding some value to it, for example, converting agricultural waste into briquettes that can be used as fuel at domestic and industrial level. Disposal of waste must be done only when the waste material is nonbiodegradable, inert and that is not at all suitable for recycling in landfill sites following systematic procedure. The management treatment of different types of waste from different sources is illustrated in Table 32.3.

32.4.1 Management Methods of Waste Related to Agricultural Purpose

Different type of wastes whether hazardous or non-hazardous coming from various sources contain nutrients for soilenrichment and those should be properly managed for their economical utilization. Agro-industrial waste, farm waste, industrial waste, municipal waste, sewage sludge, etc. comprise variable percentages of biodegradable organic matter, macro and micronutrients and mostly high percentage of moisture (60–90%). Waste utilization on agriculture is done under integrated nutrient management systems. It can be achieved either by direct application or through eco-friendly approaches under conservation agriculture. Nutrient recovery or enrichment from the waste is done by applying scientific conversion methods such as composting, vermicomposting and anaerobic digestion. Compost and slurry generated after the pathways help in sustainable recycling of nutrients to improve soil quality.

Composting is the process of transformation of organic materials like agricultural and commercial wastes to humus by using micro- and macroorganisms. The quality of the compost can be enhanced by adding fertilizers (N:P:K). Process involves mainly four stages, namely mesophilic stage, thermophilic stage, the cooling stage, curing stage (www.fao.org). In mesophilic stage certain bacteria increase the temperature of organic pile to 44 °C in order to enhance the decomposition process. Slowly it will be overtaken by thermophilic bacteria raising temperature up to 70 °C and entering into second stage of composting. At the end of second stage, where almost decomposition done thermophilic bacteria are replaced by various fungi and macro-organisms like earthworm and bugs taking the partially decomposed compost into cooling phase and then the final stage where curing and ageing of compost is done. Composting depends on various factors like substrate C:N ratio, temperature, moisture content (Argun et al. 2017). *Anaerobic digestion* of composting is the decomposition of organic materials in the absence of oxygen by micro-organisms producing numerous byproduct gases like methane (CH_4). This method of composting is time consuming but unlike aerobic method it needs lesser maintenance and nutrient status is also comparatively higher in this composting (Valentinuzzi et al. 2020). In *vermicomposting* method of composting, earthworm species like *Lumbricus rubella* and *Eisenia foetida* are used to decompose the organic wastes. The castings of earthworms are rich source of nitrate, phosphorus, potassium, calcium and magnesium compared to other composts. *Biochar* is another form of charcoal based material, can be produced from the organic waste and applied to soil to improve its quality. Biochar is produced through pyrolysis process with incomplete combustion in little or no presence of oxygen at high temperature. The heterogeneous organic waste produced from forest and agricultural fields (Rawat et al. 2019) can be converted to biochar which is also good for soil health and increases the available nutrients content in soil and growth of the crop (Pandit et al. 2019). It also reduces the environment pollution level by 60–70%.

32.5 Application of Solid Waste for Soil Quality Improvement

There are several known SW generated from household and agricultural activities and industry (crop residues, compost, manure, biochar, peat, blood meal, bone meal, wood ash, fly ash, saw dust, waste mica and sewage sludge), usually applied to soil to improve soil fertility. Application of those SW basically improves soil properties (physical, chemical and biological), increases the production, productivity and quality of grains as well as plants and ultimately improves soil quality. Therefore, an attempt has been made to understand the effect of solid wastes on physical, chemical and biological properties of soil.

32.5.1 Soil Physical Properties as Affected by Application of Solid Waste

Various researches have been conducted to see the effect of different solid wastes on soil physical attributes such as bulk density (BD), soil moisture content, compaction characteristics, permeability, soil aggregation, hydraulic conductivity, water holding capacity (WHC), etc. It is necessary to understand the effect of these solid wastes or waste derived amendments on the soil physical attributes which have a direct impact on the soil quality. Organic agro-residues can contribute to the improvement in soil physical characteristics by increasing soil aggregation due to potential binding agent in form of organic matter which is the main constituent that binds mineral particles together (Li et al. 2016). Application of CR with higher C/N ratio, like residues of rice and wheat (C/N = 105), is more lignified and slowly degradable (Klotzbücher et al. 2011), thereby, application of those CR modifies certain physical properties which can last for a longer time. Retention of CR improves storage of soil water by decreasing runoff losses, reducing evaporation and sudden fluctuations in soil temperature, enhancing infiltration rate and increasing level of SOM.

Continuous application of compost to soils where agricultural practices are carried out was found to increase the water infiltration rate (Brown and Cotton 2011), hydraulic conductivity, WHC, BD, pore size distribution, total porosity, soil penetration resistance, soil aggregation and aggregate stability (Schwartz and Smith 2016). Generally, incorporation of organic amendments in the form of compost increases soil WHC, soil porosity, percolation and water infiltration while decreases BD and soil crusting which are related to the direct and indirect effects of SOM transformation (Li et al. 2018). The enhanced biological activity due to the incorporation of biodegradable organic materials present in the SW (Njoku 2015) plays a crucial role in the reduction of soil BD. Erana et al. (2019) found that application of agro-industrial waste compost significantly improves different soil physical properties and maintains soil porosity either directly by addition of high resistance and slowly biodegradable ligneous matters or indirectly through addition of humic material after subsequent transformation of the initial OM. The enhanced OM level of soil due to compost application facilitates the formation of soil aggregates and improves soil structure. Application of MSW improves soil air filled porosity, hydraulic conductivity, BD and soil structure (Ubuoh 2012; Taddese 2019). The decrement in BD with SW application is due to the addition of lower dense organic material with the more dense mineral fraction of the soil. However, soil particle size distribution has not been remarkably altered by the effect of MSW application.

Application of biochar reduces soil BD, increases soil porosity, aggregates stability and available water content and improves soil consistency. The saturated hydraulic conductivity in course-textured soils decreases, and in fine-textured soil, increases due to biochar application (Humberto Blanco-Canqui 2017). When biochar is mixed with coarse-textured soil, it could substantially reduce the water infiltration rate and hydraulic conductivity due to the blockage of soil macro-pores with fine particles of biochar. The porous nature of biochar particles temporarily increases pore size distribution of soil (Andrenelli et al. 2016). Therefore, biochar application is more suitable in coarse-textured soils compared to fine one (Omondi et al. 2016). Conversely, fly ash application in coarse-textured soils can improve soil BD, aggregation, infiltration, WHC and hydraulic conductivity (Skousen et al. 2013). Addition of higher doses of fly ash can change the surface soil texture, usually by increasing the silt content (Garg et al. 2003) since fly ash particles are mostly in silt size ranges from 2 to 50 microns (Gangloff et al. 2000). It was also found that incorporation of fly ash at a rate of 70 t ha^{-1} is sufficient to change the soil texture from sandy and clayey to loamy (Fail and Wochock 1977). Mixing fly ash with soil can change soil texture from clay loam to sandy loam and from sandy to loamy sand (Dhindsa et al. 2016). The large surface area of the fly ash particles increases soil microporosity, thus, enhances soil WHC (Shaheen et al. 2014).

32.5.2 Soil Chemical Properties as Affected by Application of Solid Waste

Most of the SW are complex carbon-based compounds; therefore, application of those wastes adds primary, secondary and micro-nutrients to the soil, reduces heavy metal loading of contaminated soils. Nowadays, use of the treated solid wastes as soil amendment has become an unconventional alternative solution for valorization and also has the potential to improve soil health (Mandal et al. 2016) in a cost-effective way (Zoghlami et al. 2016).

32.5.2.1 Soil Organic Carbon

Decline in organic matter content of soils due to intensive agricultural practices coupled with soil erosion became a major concern regarding soil quality deterioration. Therefore, this is the high time for adaptation of sustainable management of SW that increases the organic matter content and further improves soil productivity *vis-a-vis* quality which is the utmost goal for sustainable agriculture.. Treated solid wastes application significantly improves the soil organic carbon (SOC) status which further influences various soil physico-chemical and biological properties. It is well known that the build-up of soil carbon (C) depends on the relationship between C inputs (addition) from different sources and the rate of decomposition (removal or breakdown) of soil C by various soil processes. This equilibrium between C inputs and its decomposition rate (output) highly depends on the types and quality of added C inputs and their rate of conversion into stable C (Kallenbach et al. 2016). Crop residues are a source of relatively labile C, in soil, while biochar is considered as recalcitrant or stable C and can ensure soil C sequestration (Steinbeiss et al. 2009). Further, soil labile C pool promotes microbial activity and nutrient cycling and their turnover times range from a few days to several months. Thus, labile C pool is also considered as early sensitive indicators of soil quality (Xu et al. 2011; Blanco-Moure et al. 2016). Regular application of compost, biochar, manure, crop residues, etc. increases dissolved organic carbon (labile pool of carbon) (Gong et al. 2009; Xu et al. 2011; Liu et al. 2014) as they promote soil microbial population in soil during their decomposition. Domínguez et al. (2019) reported that compost addition improved total organic C and N contents in soil. Besides, regular addition (retention or incorporation) of crop residues in the field serves as a source of plant nutrients, SOC maintaining improved soil fertility status. Continuous application of farmyard manure (FYM) and combined application of rice residue with N fertilizer for over 11 years enhanced soil organic carbon (SOC) content by 34 and 84%, respectively, and has beneficial effect on soil C sequestration as FYM and crop residues provide a source of organic C in soil (Benbi et al. 2012). Conservation agriculture (CA) with residue retention also known to improve labile soil C pool compared to the conventional practices (Das et al. 2020). This might be due to the higher topsoil microbial populations quickly mineralized carbon and nitrogen in residue-amended plots leading to higher labile carbon. Recently, biochar application for soil quality improvement is very popularized as it has a soil carbon sequestration potential as well to mitigate the ill-effects of greenhouse gas emission (Lehmann et al. 2006; Woolf et al. 2010). Moreover, biochar addition in soil not only rapidly enhances soil carbon pool, but also improves crop biomass as it has characteristics with high thermal stability coupled with strong adsorption capacity, porous molecular structure (Golberg 1985;Whalley et al. 2006; Laird et al. 2009; Yang et al. 2020). Further, application of biochar in soil is reported to enhance overall soil quality (Steinbeiss et al. 2009); however, the effectiveness of biochar depends on type and quality of raw materials used production techniques, characteristics and rate of application and type of soil (Zimmerman et al. 2011). Apart from this, press mud, sugarcane byproducts, nowadays, is also used as an organic manure to improve soil quality by showing a significant increase (150%) in the organic C and thereby reducing impact of global warming (Krishnaveni et al. 2020) because it contains high amount of fibre, cellulose, hemicellulose, organic C along with macronutrients (N, P, K, Ca and Mg) as well as micronutrients (Zn, Fe, Cu, Mn) (Patil et al. 2018). Similarly, when MSW compost having higher concentration of organic C and organic and inorganic N (Crecchio et al. 2001a, b) applied to soil, it has potential to improve soil physical (such as water retention capacity or soil structure, etc.), chemical and biological properties and can enhance soil as well as plant quality (Weber et al. 2004). There are a variety of SW products that are also known to improve soil carbon content vis-avis soil quality (Table 32.4).

32.5.2.2 Nutrients Availability and Nutrient Transformation

Nowadays, various treated solid wastes are directly applied to the soil to improve soil quality as they are usually rich in macro (especially in N and P) as well as micronutrients. Conversion of SW to compost reduces its bulk volume and improves its

Table 32.4 Solid waste management products, those are also known to improve soil carbon content vis-a-vis soil quality

Solid waste management product	Soil quality parameters	References
Municipal solid waste compost	Organic carbon and soil N, soil nutrients, boron, zinc and copper	Eriksen et al. (1999), Crecchio et al. (2001a. b), Meena et al. (2019), Ayilara et al. (2020)
Blood meal, bone meal, chicken manure, farmyard manure, byproducts of olive industries and poultry manure	Organic carbon, N, Fe, soil pH, EC, soil quality parameters, soluble and exchangeable-K^+ as well as CEC of soil	Ciavatta et al. (1997), Mondini et al. (2008), Walker and Bernal (2008), Citak and Sonmez (2011), Assefa and Sisay (2019)
Biochar, fly ash, sewage sludge	Ph, EC, N, organic C, soil enzyme	Masto et al. (2012), Ram and Masto (2014), Antonkiewicz et al. (2020)
Bagasse ash, rice husk ash, rice straw and husk (crop residue), press mud	Particulate and mineral associated organic matter, easily oxidizable carbon pool, silica and organic carbon and nutrient contents of soil, soil P	Dotaniya and Datta (2014), Ghorbani et al. (2013), Dotaniya et al. (2016), Benbi et al. (2017), Hossain et al. (2018), Baiyeri et al. (2019)
Waste mica	Total organic carbon, labile C pool, available K	Biswas et al. (2018), Basak (2019)

nutrient status. Therefore, application of compost to soil increases the soil nutrient status as well as minimizes environmental pollution by reducing heavy metal loading of contaminated soils (Atalia et al. 2015). In many countries, the farmers applied FYM in their fields as a major organic amendment to maintain soil quality (Lakhdar et al. 2010). Applied FYM in soil acts not only as a source of nutrients but also influences the availability of nutrients to crops by contributing to nutrient pool and also by influencing the soil physical, chemical and biological properties. During decomposition of organic materials like FYM, compost, etc. in soil, organic acids formed leading to the transformation of soil nutrients, i.e. solubilization, mobilization or immobilization, besides enhanced proliferation of soil microbes. The benefits of FYM, compost, crop residue retention vary from region to region depending on both agroclimatic condition and various socio-economic factors. The retension of crop residues has positive impact on soil quality in terms of improved soil organic carbon storage, soil moisture conservation, improved nutrient recycling, reduced soil loss, etc. The negative impact includes nutrient immobilization, water stagnation, soil temperature fluctuation, etc. (Turmel et al. 2015). Many studies have shown that application of FYM, compost, crop residue in soil has significant impact on soil pH, CEC,C/N ratio of soil, nutrients concentration especially P due to the physico-chemical properties of the residue and variable soil properties (Zibilske et al. 2002; Xu and Coventry 2003; Govaerts et al. 2007; Butterly et al. 2011). Biochar application increases water retention capacity of soil, reduces leaching of nutrients and soil acidity, minimized emissions of nitrous oxide, increased cation exchange capacity (CEC) of soil, improving soil fertility, influenced seed germination *vis-avis* early growth of seedlings and crop production (Tripathi and Melo 2018). A lot of researchers reported that fly ashes having high concentration of elements like potassium, sodium, zinc, calcium, magnesium and iron influence crop yield. On the contrary, Sharma and Kalra (2006) reported that application of fly ash sometimes leads to reductions in the crop yields due to toxic accumulation of B, Mo, Se and Al. Further, Petruzzelli et al. (1986) stated that application of fly ash in soil reduced the uptake of heavy metals like Cd, Cu, Cr, Fe, Mn and Zn in plant tissues which might be attributed to the increased soil pH. Basu et al. (2009) also reported several other use of fly ash to improve soil quality (such as source of nutrients, compost, soil amendment, chemical fertilizers, pesticide, etc.). Besides, press mud is also reported to improve soil physico-chemical properties having higher concentration of organic C micronutrients (Zn, Cu, Fe and Fe) in its composition. Therefore, these can be also partially substituted for inorganic fertilizers to increase soil nutrients content (P, K, Ca and Mg) (Mays et al. 1973; Pinamonti 1998). The following are some other solid waste management products that are also known to improve soil carbon content vis-a-vis soil quality.

32.5.2.3 Waste Management for Heavy Metal Immobilization

Prominent emanation of heavy metals occurs due to anthropogenic and natural processes and they eventually end up in the ecosystemic components including soil, air, water and/or at their interfaces. Heavy metals by nature are potentially toxic elements and their toxicity is expressed when they are not metabolized by the body and subsequently accumulate in soft tissues. These elements enter the human body either through food, water and air or are absorbed directly through the skin upon contact with people from the field of agriculture, pharmaceuticals, industries and even in residential areas. Notably, soils are the major sinks for heavy metals released into the environment and most heavy metals do not undergo chemical or microbial degradation, consequently enhancing their residence time in the environment, esp. in soils. These heavy metals not only adversely affect the yield of crops but also can be taken up by plants which lead to the contamination of the food chains, thus affecting the entire ecosystem adversely.

Many studies reported that application of organic amendments generated from agro-industrial wastes helps in immobilization of toxic metals in soil and reduced their bioavailability to plants (Sabir and Zia-ur-Rehman 2015). This immobilizing capacity of organic residues is mainly due to the presence of acidic functional groups which bind to wide range of metal(loid)s, viz. Pb, Cd, Cr and Cu (Alvarenga et al. 2009). Biosolids, composts and manures from different biowastes, rice husk, straw, saw dust and wood ash are the most commonly used soil amendments to immobilize toxic metals in soil (Karaca 2004; Sabir and Zia-ur-Rehman 2015). Reportedly, pH is an important factor which influences the mobility of metals in soil (Huang et al. 2016). Soil pH influences the in-solubilization and precipitation of toxic metals and also affects the formation of insoluble organic complexes (Walker et al. 2004). Thus, soil pH and organic matter content are the vital factors which may control the formation of metal complexes and influence their bioavailability to plants. The strong negative charge generated on the OM surfaces through the dissociation of organic acids strongly binds the positively charged metal in soil. Therefore, application of OM through SW enhances the fixation of toxic metals and reduces their mobility and phytotoxicity (Achiba et al. 2009; Hamdi et al. 2019). It is noteworthy to report that application of mature and stable compost prepared from green wastes may lead to immobilization of heavy metals through formation of complexes with surface functional groups, viz. OH and COOH. However, direct application of agro-industrial wastes or application of immature composts may impart negative effect on crop growth as they contain relatively high soluble OM content (Huang et al. 2016). Therefore, it is important to take necessary care during imposing remediation measures of multiple heavy metal contaminated soil through application of agri-industrial wastes.

Conventional technologies for the removal of these toxic heavy metals are not economical and further generate huge quantity of toxic byproducts. Thus, biosorption is a potential alternative to these existing technologies for the removal and/or recovery of metal ions from their aqueous solutions (Sud et al. 2008). The mechanism of biosorption includes adsorption on surface, chemisorption, complexation, diffusion and ion exchange. Therefore, selection of any suitable amendment is crucial to efficient immobilization of heavy metal ions. Biosolids are reportedly effective sinks for heavy metals, thus reducing their bioavailability in contaminated soils. Shaheen et al. (2017) reported that biosolids can immobilize Cu, Cd, Pb and Zn in soils with higher metal concentration. In a leaching column experiment conducted on soils contaminated with Cd, Tapia et al. (2010) found that composted biosolids can effectively immobilize Cd. Placek et al. (2016) conducted a field study on the effect of biosolids on heavy metal mobility and found that the application of biosolids increased the values for soil parameters like pH, CEC and humic acids content, thus enabling Cd, Zn and Pb immobilization while facilitating the simultaneous growth of plants by providing plant macronutrients like N and P. Nandillon et al. (2019) used a mining technosol contaminated by arsenic (1068 mg kg^{-1}) and lead (23,387 mg kg^{-1}) to study the effect of three amendments (biochar, compost and iron grit) on metal(loid) mobility and their bioavailability and bioaccessibility. The combination of the three amendments resulted in a significant decrease in As and Pb concentrations in clover tissues, mainly in the aerial organs. The amendments also made it possible for some of them to halve the phytoavailable fraction of heavy metals esp. arsenic. Before applying the biosolids to soil, dissolved organic matter (DM) in biosolids and other soil properties should be considered because formation of organo-metallic complexes with DM derived from biosolids led to decreased metal sorption esp. Ni, Cu and Pb in soil amended with biosolids compared to unamended soil (Liu et al. 2007).

Constituent compounds in compost, viz. humic substances, mineral ions and microorganisms can effectively enhance heavy metal immobilization in agricultural soils, thus reducing the environmental risks associated with heavy metals (Udovic and McBride 2012). Huang et al. (2016) reported that plant-derived composted organic amendments can be used to immobilize heavy metals in contaminated soils. After compost application, different heavy metals showed variable responses. For example, the affinity of OM for As is less compared to other cationic metals (Fleming et al. 2013). In an experiment by Fuente et al. (2011), they demonstrated that application of compost of olive husk reduced the availability of Pb by forming complex with humic substances. Zhou et al. (2012) also added that addition of agro-industrial waste based composts in alkaline soil could reduce the available Pb burden in agricultural soil. While application of FYM not only reduced heavy metal content in soil but also reduces its uptake in plant (Alamgir et al. 2011). Mehmood et al. (2017) reported that applying commercial compost may decrease the As sorption sites in soil and more specifically in clay loam soils. The higher clay content and CEC of such soils led to an increased negative charge on soil colloids and As oxyanions for sorption on soil colloids increased As mobilization in the soil due to anion expulsion (Mehmood et al. 2017). When applying compost, the heavy metal content and other soil chemical properties along with soil type need to be carefully considered for heavy metal immobilization. Also, the co-vermicomposting process may be used to decrease hazards due to heavy metals since earthworms have been found to be efficient bio-accumulators of heavy metals (Wu et al. 2020). Crop residue retention and incorporation into the soil is strongly encouraged rather than burning them to minimize air pollution and for agriculture sustainability. Several studies have been conducted to investigate the effects of plant residue management on soil quality and heavy metal immobilization. Incorporation of rice straw either dried or composted into the soil is a common practice in uplands or even in lowland farming. Shu et al. (2016) studied the Hg mobilization in rice straw treated soils in different forms, i.e., dry straw, composted straw, straw biochar and straw ash. They found that composted straw decreased phytoavailability of methyl-Hg, indicating methyl-Hg immobilization. This was attributed to methyl-Hg strongly binding with particulate OM in composted rice straw. Zhang et al. (2018) found that rice straw incorporation resulted in a 28–136% enhancement in methyl-Hg levels in paddy soil Hg-contaminated. Plant residues have varying effects on heavy metal immobilization depending on maturity levels and composition of material as well as soil properties.

Biochar has been found to immobilize heavy metals in contaminated soils while improving soil quality with a reduction in crop uptake of heavy metals (Palansooriya et al. 2019). Ahmad et al. (2017) observed a significant reduction in Pb and Cu leaching in alkaline soil under application of biochar produced at a temperature of 300 °C through mechanisms like surface complexation and precipitation. In acidic soils, they encountered complete reduction in mobility of Pb and Zn with biochar produced at a temperature of 700 °C. Results from a greenhouse pot experiment conducted by Shaheen and Rinklebe (2015) showed that coal fly ash application reduced soluble and exchangeable Pb in contaminated soils significantly leading to a prominent reduction of Pb in plant tissue. It can also reduce the leaching of Zn, Cd and Pb by 41.2, 32.9 and 25%, respectively, through increasing soil pH (Houben et al. 2012). Elevated soil pH resulting from application of fly ash leads to heavy metal immobilization in many cases (Shaheen and Tsadilas 2010; Mahar et al. 2016). Most studies suggest that increased soil pH following coal fly ash application is the major reason for heavy metal immobilization in soil. In contrast, fly ash may not always be effective in immobilizing heavy metals owing to heavy metal characteristics, coal fly ash heterogeneity, agroclimatic conditions and soil type (Ram and Masto 2014).

32.5.2.4 Soil Biological Properties as Affected by Application of Solid Waste

Soil is such an important natural resource which is the only natural medium for culture and production of plants or crops ultimately consumed by the animals and human beings for their survival. Soil itself is considered to be a living entity owing to the vast community of micro and macro fauna and flora residing in it. Although microbial biomass constitutes minute proportion (1–5%) of the total carbon, nitrogen, sulphur and phosphorus pool in organic matter of arable soils, microbiological properties can be considered as sensitive indicators of soil quality. Microbial biomass carbon links soil nutrients to energy transformation dynamics and has been reported to respond to even short-term soil changes from the nutrient supply and environmental point of view (Haynes 2008). Addition of treated biodegradable solid organic wastes generated from cities (municipal solid wastes), agricultural practices (manures, compost and also as crop residues), industries *esp.* agro-based industries (fly ash, sugar industry and distillery effluents) greatly affects the activity and diversity of soil microbes as well as soil quality (Liu et al. 2013).

Soil Microbial Biomass and Diversity

Soil biological parameters such as microbial population, microbial biomass C (MBC) and (MBN), basic respiration (BR) or even enzyme activities have been widely used to measure the effects of different types of waste management techniques on the soil microbiota (Schloter et al. 2003). The natural microbial biomass can be an indicator of soil fertility, and an increase in biomass indicates improvement, whereas a biomass decrease suggests possible soil degradation (Kushwaha et al. 2000). The crop source and quality of on-farm crop residues used for soil management can also influence the microbial population and community structure (Wardle and Lavelle 1997). Cereal straw resulted in a higher population of cellulolytic fungi (Eitminaviciute et al. 1976), which was probably because of the higher ability of fungi, for residue decomposition when the residues have a lower nitrogen content (Burns 1982). Greater microbial activity due to residue management was reported by Cookson et al. (1998) who found higher bacterial and fungal densities at varying residue decomposition rates with wheat residues. Tillage and residue management practices influence the microbial diversity of soil and manipulate the soil nutrient cycling (Spedding et al. 2004). Plant residue retention at soil surface under conservation agriculture encourages higher fungal growth (Balota et al. 2003; Pankhurst et al. 2002). Soil microbial properties like MBC, MBN, microbial respiration, metabolic quotient can respond to crop residue management practice within a few years under changing climate (Pankhurst et al. 2002). In addition to agro and horticultural waste management and tillage practices, local/regional climatic conditions can also play a role in governing soil microbial properties and sustainable growth in crops (Pampuro et al. 2017; Joardar and Rahman 2018). Manures and compost prepared from on-farm or off-farm wastes can prove equally useful techniques of waste management and used as soil quality enhancing amendments in the field of agriculture. Malik et al. (2012) conducted an experiment to examine the effects of farmyard manure (FYM); poultry litter (PL) and biogenic waste compost (BWC) on microbial biomass and activity. All the three amendments increased microbial biomass C, N and P and dehydrogenase activity. The type of organic wastes, the degree of their stability and their chemical constitution markedly affect MBC an MBN in soil (Jedidi et al. 2004).

The microbe-mediated processes in the soil are disturbed by the application of pollutants such as fly ash which are the byproducts of power generation industries leading to the imbalance of ecosystem (Murugan and Vijayarangam 2013). Pitchel and Hayes (1990) reported an increased content of fly ash leads to a decrease in the total bacteria, actinomycetes, fungal species. A decrement in the microbial biomass and enzyme activities due to the application of sewage sludge into the soil was also observed in some studies by Kao et al. (2006), whereas in another research soils, amended with sewage sludge resulted in an increase in soil respiration and microbial activity (Banerjee et al. 1997). The microbial population which includes bacteria, fungi and actinomycetes, MBC and MBN were found to increase in soils to which press mud and vinasse were applied and the results were better in comparison to chemical fertilization (Yang et al. 2013). Meena and Biswas (2014) reported a significant enhancement both in microbial biomass and MBC in soil amended with compost prepared using phosphate rock and mining industry wastes like waste mica in conjunction with chemical fertilizers at half of their recommended dose. Microbial activity was consequently found to affect soil nutrient availability upon addition of organic matter or amendments with high organic matter content (Gichangi et al. 2009). Rajput et al. (2019), from their observed results, concluded that combined application of wheat compost or wheat + rice compost with inorganic fertilizers serves the best management option for sustainable rice agro-ecosystem in hilly uplands and positively affected the biological health of soil.

32.5.2.5 Soil Enzymatic Activity

Soil enzymes play a key biochemical role in organic matter decomposition, soil structure stabilization, cycling of important plant nutrients (Dick et al. 1994). Enzymatic activity in soil has always been an effective indicator of the microbial functions. Dehydrogenase happens to be the most studied enzyme owing to its occurrence in every viable microbial cell, thus determining the overall soil microbiological activity (Nannipieri et al. 2011). Dehydrogenase activity has been reported to be responding significantly to organic waste management treatments and stages of crop growth along with their interactions in the soil system. The oxido-reductase reaction which is carried out by soil dehydrogenase depends largely on the availability of substrate and the presence of organic matter substrate in compost prepared from solid wastes and biochar had a positive effect on the microbial biomass and the microbial activity as a whole (Elzobair et al. 2015). Alkaline phosphomonoesterase/phosphatase (AP) is the key enzyme responsible for transformation of phosphorous owing to its role in phosphorous mineralization (Richardson et al. 2001). While AP activity reportedly depends on several factors like organic amendments, soil properties and microbial interactions (Speir and Ross 1978) it was found to be significantly influenced by organic amendments and crop stages. Zhang et al. (2016) validated the results that solid waste amendments rich in organic matter enhance the soil alkaline phosphatase activity. Saha et al. (2008) found that though FYM addition significantly improved the activity of different soil enzymes such as dehydrogenase, carbohydrate, alkaline and acid phosphatases, protease and cellulase, but the activity of urease was not affected. Combined application of FYM and inorganic fertilization improves soil biological characteristics and increases biological activity, i.e., the activity of glucosidases and microbial respiration even in the deeper parts of soil profile up to 60 cm soil depth (Holík et al. 2019).

Improvement in soil biological properties was higher when vermicompost is prepared from cow dung and can increase soil MBC, urease, dehydrogenase, phosphatase, β-glucosidase and arylsulfatase values by 28.3, 12.6, 25.9, 12, 26 and 14.2%, respectively, rather than prepared from green forages (Tejada et al. 2010). It was also found that vermicompost has the potential to be used as a substitute of FYM to improve and maintain the microbial activity even in alkaline calcareous soils of Mediterranean region of Turkey (Uz and Tavali 2014). Compared to the alone application of mineral-fertilizer combined application of vermicompost and mineral fertilizers increased the total organic C and MBC, b-glucosidase, alkaline phosphatase and dehydrogenase thus improves soil fertility and supports better plant growth (Srivastava et al. 2012).

Pitchel and Hayes (1990) reported that increased content of fly ash decreases the soil enzymes such as phosphatase, sulphatase, dehydrogenase and invertase. Soil amended with fly ash stimulates the soil enzymatic activity including the activity of enzymes like dehydrogenase, urease and phosphomonoesterase (Pati and Sahu 2004). A decrease in the activity of dehydrogenase and catalase was also observed with fly ash application at a higher rate which may be attributed to an increase in soil pH and associated dilution effect on the organic compounds (Lai et al. 1999). When the possible utilization of some of the other industrial waste products was considered, the activity of different enzymes such as phosphatase, cellulase and aminopeptidase was higher with press mud treatment compared to the chemical fertilizer. Hence waste products like press mud and vinasse can be used as potential substitutes to chemical fertilizer owing to their potential to improve soil health and since they can be disposed to the environment without any ill-effects (Yang et al. 2013).

32.6 Policies and Schemes for Management of Solid Waste in India

The Government of India (GOI) has started number of initiatives to mitigate the problem of SW management during the last two decades. Back in 1960s Ministry of Food and Agriculture initiated a scheme for credited loan to convert SW to compost. The J.S. Bajaj Committee constituted by the Planning Commission in 1995 gave a wide range of recommendations regarding waste collection, transportation and its subsequent conversion to compost (CPHEEO 2016). According to the Solid Waste

Management, Rules 2016, composting is considered most important technique to SW management in cities. Some of the policies and schemes initiated by GOI would help the farmers who are the backbone of our country. So seeing from side of economy of the country, farmers are burning the resource biomass due to the economic and social problems such as lack of awareness and knowledge. Therefore, collection of crop residue by government and efficient utilization is required. During the past few years, central and state Government of India has been given much more attention on SW management. One such scheme proposed by Government of India is 'programme of energy from urban, industrial, agricultural wastes/industrial, municipal solid waste' in the form of waste to energy concept. In this project they have used some agricultural waste in such a way to promote biomass gasifier for feeding power into the grid or meeting captive power and thermal needs of rice mills/other industries and villages. To reduce the practice of crop residue burning in Punjab and Haryana, a new Central Sector on 'Promotion of Agricultural Mechanization for In-situ Management of Crop Residue' has been proposed by GOI for creating awareness among the farmers and in the States of Punjab, Haryana, Uttar Pradesh and NCT of Delhi for the period from 2018–2019 to 2019–2020. Mass awareness campaigning has been done through KVK among the farmers and they have performed some on-farm techniques to manage the residual waste and successfully convert 25 villages into zero stubble villages in 2017, that has been increased to 76 villages in 2018–2019 in Punjab (Bhuvaneshwari et al. 2019). National Thermal Power Corporation (NTPC) has been directed by Government of India to mix crop pellets (10%) with the coal for the purpose of power generation which will help the farmers to curb the crop residue burning.

32.7 Conclusions

Waste management is as important for the environment as it is for the human and animal health. Human health largely depends upon the purity, cleanliness and decontaminated sustainable management of the natural resources which if not used judiciously may have an adverse impact on the ecological balance. Therefore, management of solid waste for improving soil fertility and quality is very important for sustainable development of agriculture and society. One of the most effective ways to manage the huge quantity of solid waste is by converting them into nutrient-rich compost, manure and biochar. Besides, agricultural wastes like crop residue, molasses, bagasse, press mud, etc., industrial waste like biosolids, waste mica, fly ash and other MSW are also rich in C and available plant nutrients. Those nutrient-rich waste products have the potential to be used as an alternative nutrient source to the chemical fertilizers and can effectively improve the physical, chemical and biological properties of soil although the extent of such change of soil properties largely depends on the chemical composition and the stability of the applied wastes. Thus, proper treatment of SW is very important before its soil application and it is necessary to ensure the effective solid waste management and conversion systems for application in soil. Policy support to scale up production and consumption of compost, vermicompost, manure, biochar and biosolids is imperative to develop within the existing framework. Fertilizer control norms, testing laboratory facilities, stringent targets for fertilizer companies are indispensable for efficient and safe application of waste in agriculture in the view of soil health. It can be concluded that SW management through soil application for improvement of soil quality is a win–win approach which not only helps in management of the natural resources in a sustainable manner but also helps ensure socio-economic development of the country as a whole.

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33 Nutrient Sufficiency Range of Soils and Plants in Singapore

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Abstract

Plants rely on soil as the primary source of available nutrients for their growth and health. Soil and plant analyses as a diagnostic tool for assessing the sufficiency and deficiency of nutrients are well established. However, the sufficiency nutrient range for soils and plants in Singapore and the region is less documented. Sufficiency range is a measure of the concentration of nutrients range that lies between deficiency value and an excess concentration both in soils and plants. Establishing nutrient sufficiency ranges are important for a correct evaluation of plant nutrition. This chapter highlights the nutrient ranges that were developed in Singapore for soils and selected leafy vegetables and horticulture plants.

Keywords

Nutrients · Sufficiency range · Plant analysis · Nutrient sufficiency · Interpretation

33.1 Introduction

Singapore is a biophilic city in a garden that is moving towards a "City in Nature" by integrating nature into the cityscape to strengthen Singapore's distinctiveness as a highly liveable city while mitigating the impacts of urbanisation and climate change. More than 40% of Singapore's total land area is covered by vegetation of which about 26% is managed vegetation (Edwards et al. 2020). In recent years, Singapore

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has been adopting biophilic designs in restoring habitats and engaging the community to sustain the greening efforts. In this push, the National Parks Board has been at the forefront to enhance nature. Soils in the urban landscape provide various ecological functions and play pivotal role for sustainable environmental management (Ghosh et al. 2016a, b). However, there is a paucity of information on the heterogeneity and composition of soils in Singapore and how these might influence or underpin ecological processes and functions (Tan and Hamid 2014). Majority of the studies on soils in Singapore are predominantly focussed on civil engineering applications (Bo et al. 2015; Rahardjo et al. 2004; Zhai et al. 2016). Outside of the primary and secondary forests, the soils of Singapore have seen extensive anthropogenic activity. Though several studies (Burslem et al. 1994; Grubb et al. 1994; Leitgeb et al. 2019) have been done on forest soils of Singapore, soils outside these areas have not been studied extensively for its fertility status and nutrient levels of plants. Consequently, published work on sufficiency range of nutrients in soil and plants is lacking.

In a first attempt to evaluate the soil quality (physical, chemical and biological) for roadside soils of Singapore, Ghosh et al. (2016a, b) studied the influence of soil properties on street tree attributes in Singapore's streetscapes, a narrow area of tree planting strips of at least 2 m $\times$ 1 m and filled with engineered soils (Approved Soil Mix (CUGE Standards 2013)). They concluded that the variation in soil properties by depth and across Singapore's streetscapes was minimal and was not limiting for trees and attributed it to the generally uniform soil mixes that were used for planting. Although there is a need to develop nutrient sufficiency range for plant and soil in Singapore in order to provide recommendations for general horticulture and arboriculture, but literature pertaining to studies across other landscapes and parks are not available to help form a generalised soil sufficiency range that can help horticulture professionals to make sense of soil and leaf tissue test data. The chapter highlights the sufficiency range of nutrients in soil and selected plants that was developed by the Soil Management Laboratory of National Parks Board, Singapore.

33.2 Nutrient Sufficiency Range

Nutrient sufficiency is a relative term that is a measure of the concentration range both in soils and plants of a given nutrient that lies between critical deficiency value and an excess or toxic concentration and ideally, it is given as a concentration range rather than a single concentration (Sharawat 2006). There are 17 elements considered essential for plant growth: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), iron (Fe), boron (B), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), chlorine (Cl) and nickel (Ni). Carbon, H and O are assimilated by the plants and the mineral nutrient elements are classified as macro (N, P, K), secondary (Ca, Mg, S) and micronutrients (Fe, B, Mn, Cu, Zn, Mo, Cl, Ni). The range of concentrations at which the nutrient supply is sufficient for ideal and optimum plant growth is termed the nutrient sufficiency range (Fig. 33.1). Deficiency and declined plant

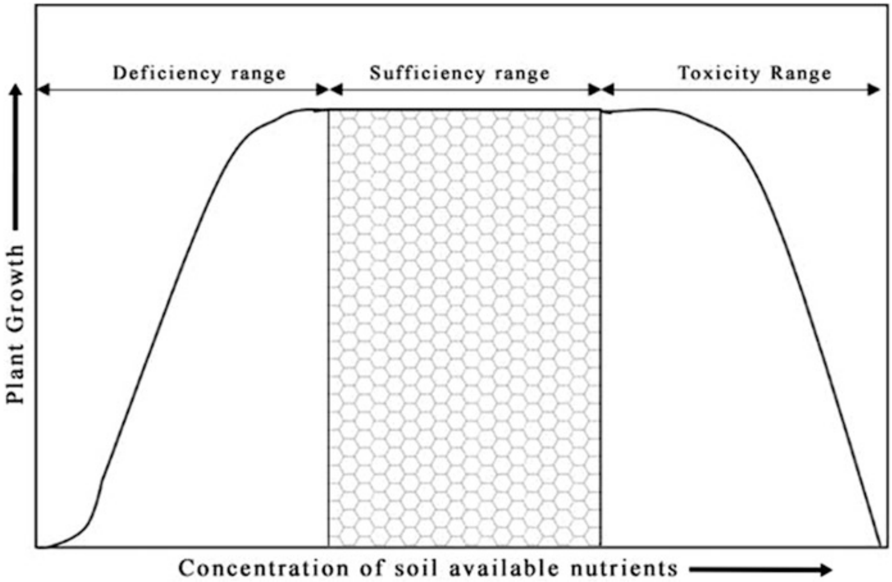

Fig. 33.1 Relationship between concentration of soil available nutrients and plant growth (Brady and Weil 2008)

growth may arise at low concentration level of these nutrients. When the nutrient concentration increases, plant can acquire the nutrients they require within the sufficiency range for optimum growth (Brady and Weil 2008). At higher concentration of available nutrients, the plant takes up too much nutrient which may lead to reduced plant growth either because of an imbalance with other plant nutrients or direct toxic effects of the excessive nutrient. For instance, P at high levels can inhibit the uptake of Cu and Zn and be out of balance with respect to N or K (Schulte and Kelling 2016).

The determination of nutrient sufficiency and requirements is based on the relationships with plant growth and yield. According to the sufficiency level concept, there are definable levels of individual nutrients in the soil below which crops will respond to added fertilisers and above which they will probably not respond (Eckert 1987). Thus, once the nutrient is present in sufficient quantity, plant growth will be maximal across a range of nutrient concentrations before eventually decreasing as toxic levels are reached.

The nutrient elemental composition of the plant at optimal yield should approximate the nutrient sufficiency levels, expressed either as individual nutrient concentrations or ratios of the various nutrient elements (Black 1993). The ASEAN Guidelines on Soil and Nutrient Management (2017) had highlighted generalised soil fertility ratings for agricultural soils which are being followed by several South East Asian nations (Table 33.1).

Table 33.1 Categories used in the ASEAN region to give generalised soil fertility ratings (ASEAN Guidelines on Soil and Nutrient Management (2017))

Parameter	Brunei	Indonesia	Cambodia	Lao	Malaysia	Philippines	Singapore	Thailand	Vietnam
Organic C (%)	Method: Walkley–Black Low <1.0 Medium 1.0–1.9 High ≥2.0	Method: Walkley–Black Very low <1 Low 1–2 Medium 2–3 High 3–4	Method: Walkley–Black Very low <0.4 Low 0.4–0.7 Medium 0.8–1.7 High 1.7–2 Very high >2	Method: Walkley–Black Low <0.9 Medium 1.0–1.9 High ≥2.0	Method: Combustion Low <1.4 Medium 1.5–2.9 High ≥3.0	Method: Walkley–Black Low <0.6 High 0.6–4.7	–	Method: Walkley–Black Low <1.5 Medium 1.5–3.5 High ≥3.5	Method: Walkley–Black Low <0.9 Medium 1.0–1.9 High ≥2.0
Total N (%)	–	Method: Kjeldahl Very low <0.1 Low 0.1–0.2 Medium 0.21–0.5 High 0.51–0.75	Method: Kjeldahl Very low <0.1 Low 0.1–0.15 Medium 0.15–0.25 High 0.25–0.5 Very high >0.5	Method: Kjeldahl Low <0.15 Medium 0.16–0.25 High >0.25	Method: Combustion Low <0.14 Medium 0.15–0.26 High ≥0.27	Method: Kjeldahl Low <0.1 High 0.1–0.4	Method: Kjeldahl Low <0.15 Medium 0.15–0.20 High >0.20	Method: Kjeldahl Low <0.1 Medium 0.1–0.2 High >0.2	Method: Kjeldahl Low <0.1 Medium 0.1–0.2 High >0.2
Extractable P (mg P/kg soil)	Method: Bray II Low <21 Medium 21–30 High >30	Method: Bray II Very low <4 Low 5–7 Medium	Method: Bray II Very low <15 Low 15–20 Medium	Method: Bray II Low <10 Medium 10–25 High >25	Method: Bray and Kurtz Low <10 Medium	Method: Bray I Low <6 Medium 6–10 High 7–10	Method: Mehlich 3 Low <30 Medium 30–60 High >60	Method: Bray II Low <10 Medium 10–25 High >25	Method: Bray II Low <21.8 Medium 21.8–43.6 High >43.6

		8–10 High 11–15	20–40 High 40–100 Very high >100		10–15 High >15				
Extractable K (mg K/kg soil)	Method: NH_4 Ac, pH 7 Low <78 Optimum 78–117 High >117	Method: NH_4 Ac, pH 7 Very low <10 Low 10–30 Medium 40–50 High 60–100	Method: NH_4 Ac, pH 7 Very low <5 Low 5–15 Medium 15–30 High 30–60 Very high >60	Method: NH_4Ac, pH 7 Low <60 Medium 60–90 High >90	Method: NH_4Ac, pH 7 Low <90 Medium 90–150 High >150	Method: NH_4 Ac, pH 7 Low <58 Medium 58–98 High >98	Method: Mehlich 3 Low <150 Medium 150–300 High >300	Method: NH_4 Ac, pH 7 Low <60 Medium 60–90 High >90	Method: NH_4 Ac, pH 7 Low <83 Medium 83–166 High >166
CEC ($cmol_c$/kg)	–	Method: NH_4 Ac pH 7 Very low <5 Low 5–16 Medium 17–24 High 25–40	Method: NH_4 Ac pH 7 Very low <6 Low 6–12 Medium 12–25 High 25–40 Very high >40	Method: NH_4Ac pH 7 Low <10 Medium 10–20 High >20	Method: NH_4Ac pH 7 Low <10 Medium 10–15 High >15	Method: NH_4 Ac pH 7 Low <10 Low 5–16 Medium 10–20 High >20	Method: NH_4 Ac pH 7 Low <10 Medium 10–20 High >20	Method: NH_4 Ac pH 7 Low <10 Medium 10–20 High >20	Method: NH_4 Ac pH 7 Low <10 Medium 10–20 High >20

33.3 Soil Sufficiency Range Used as Guideline for General Horticulture in Singapore

Urban soils vary greatly in terms of composition and degree of development and strongly influenced by human activities (Ghosh et al. 2016a, b). Anthropogenic activities and abrupt land use change due to urbanisation may result in poor soil condition in the urban landscape (Trammell et al. 2011). Soil testing is significant to assess the available nutrients and to make recommendations for sustainable urban soil management such as fertiliser applications (Horneck et al. 2011). Concepts in soil test interpretation differ greatly and interpreting soil test results is probably the most challenging aspect for agronomists and horticulturists. We chose to go for sufficiency range as guideline for general horticulture in the highly anthropogenic soils of Singapore. Although sufficiency range is available for agricultural soils worldwide, such range that can be used for general horticulture is scanty. The Soil Management Laboratory had worked on first approximations to develop sufficiency range of major nutrients in soils (Philip 2014) from several years of soil test results (Table 33.2).

First approximations were considered as a baseline in the absence of work with specific soil nutrients across diverse landscapes in Singapore. This soil sufficiency range is being used by the Soil Management Laboratory of the National Parks Board, Singapore for providing comments and recommendations for the soil test results.

Table 33.2 Soil parameters: sufficiency range (Philip 2014)

Test	Sufficiency range	Methods
pH (1:2.5)	5.5–7.0	Thomas (1996)
EC (1:5)	<2.0	Rhoades (1996)
Nitrogen (mg/kg)	1500–2000	Bremner (1996)
Phosphorus (mg/kg)	30–60	Mehlich (1984)
Potassium (mg/kg)	150–300	
Calcium (mg/kg)	1000–2000	
Magnesium (mg/kg)	100–180	
Sodium (mg/kg)	<100 (acceptable limit)	
Boron (mg/kg)	0.5–20	
Copper (mg/kg)	1–50	
Iron (mg/kg)	50–100	
Manganese (MnAl index)(mg/kg)	25–100	
Zinc (mg/kg)	1–50	
C:N ratio	12:1–24:1	
CEC (cmol/kg)	Low: <10 Medium: 10–20 High: >20	Sumner and Miller (1996)

33.4 Leaf Sufficiency Range of Selected Plants in Singapore

Plant analysis, as a diagnostic technique is used to determine the nutrient status of plants. It is an important tool for diagnosing and correcting plant nutrient deficiencies and imbalances (Baldock and Schulte 1996) and in turn aids in our assessment of the plant's health. Occasionally, the soil may contain sufficient nutrient levels but due to other issues such as insect feeding, root damage and environmental variables, plants are unable to take up the adequate amounts of nutrients. Plant analysis therefore complements soil testing to identify the state of nutrients in plants. Interpretation of leaf analysis results will help to identify nutrient deficiencies or excess in plant tissue and thus allowing adjustments in the fertilisation program (Malavolta et al. 1997).

Critical nutrient concentration as a basis for diagnosing plant nutrition problems is fairly well established. Several references are available for nutrient sufficiency and deficiency range of plants (Chapman 1966; Mills and Jones Jr 1996; Silva and Uchida 2000). However, authoritative reference values for acceptable leaf nutrient range are lacking in Singapore. Therefore, the Soil Management Laboratory embarked on a surveillance programme from 2009 to 2014 to test and develop the sufficiency leaf nutrient range of commonly grown ornamental plants, trees and vegetables. The data collected from this programme was compiled into a database for reference. In conjunction with soil sufficiency range (Table 33.2), the leaf nutrient range is now helping us to refine management recommendations. More commonly grown plants and tree species would be included to this database in future to enhance the guidelines.

Plants chosen to develop the sufficiency range were from the ornamental plants, trees / palms and vegetable categories. Bougainvillea, Canna, Heliconia and Ixora were chosen from the ornamental plants. From trees and palms category, Lagerstroemia, *Dypsis* sp. and *Roystonea* sp. were chosen due their prominence in avenues, gardens and landscapes. The three vegetables, Baicai (*Brassica* sp), Xiao baicai (*Brassica rapa* var. *chinensis*) and Bayam (*Amaranthus tricolor*) were chosen as they are grown extensively in the vegetable farms and community gardens in Singapore.

Healthy leaf samples were collected throughout the year from 50 locations. The leaf samples (50 nos.) were analysed to determine the macro (N, P, K, Ca and Mg) and micro (B, Cu, Fe, Mn and Zn) nutrients. Leaf samples were analysed for total nutrients by dry ashing and acid digestion followed by reading various elements using the ICP-OES. Total nitrogen was determined by the Kjeldahl method (Kjeldahl 1883). Though all samples collected and tested were from apparently healthy samples, the acceptable range of nutrients listed below was approximated at 20% on either side of the mean values. Clustering of the data was also carried out and, in some cases, the major cluster was chosen for the sufficiency range.

33.4.1 Ornamental Plants

These plants are commonly grown for aesthetics in gardens, parks and landscape design projects.

33.4.1.1 Bougainvillea

Bougainvillea is a hardy perennial shrub that blooms in a wide range of colours practically year-round in warm climates and is probably one of the most often desired plants to add colour to any landscape. Bougainvillea can be seen almost everywhere, in the planting troughs of overhead bridges, as hedges along centre dividers and avenue, as potted plants in home gardens and as shrubs in parks.

33.4.1.2 Canna

Canna (*Cannaceae*) plants have large attractive foliage and are widely grown. Many different cultivars of *C. indica* and *C. glauca* are used in landscaping of parks and gardens throughout the island.

33.4.1.3 Heliconia

Heliconia is a vigorous tropical plant that requires little attention once established. It flowers in a wide range of colours practically year-round in warm climates and is probably one of the most desired plants to add colour to any landscape. *Heliconia* is commonly planted in groups as hedges along avenue, in home gardens, housing estates and parks to impart a tropical look.

33.4.1.4 Ixora

Ixora is a medium-sized, tropical flowering evergreen shrub that is used in landscapes. The flowers grow in small clusters and come in an array of colours including red, pink and orange. *Ixora* grows best in full sun as long as they have some shade during the hottest part of the day and blooms year-round, with flower production peaking in the warm months of the year. A multitude of species, cultivars and hybrids are grown as hedges along avenue, in home gardens, housing estates and parks (Table 33.3).

33.4.2 Trees/Palms

33.4.2.1 Lagerstroemia

Lagerstroemia trees produce white, pink, mauve or purple flowers with crimped petals. Various species of *Lagerstroemia (indica, floribunda*) are planted as shrubs/ flowering trees in Singapore.

Table 33.3 Nutrient sufficiency range of four ornamental plants in Singapore (Philip *et* al (2015)

Nutrients	*Bougainvillea*	*Canna*	*Heliconia*	*Ixora*
Total N (%)	2.61–3.25	1.50–2.75	1.45–2.15	1.12–1.68
Total P (%)	0.20–0.30	0.20–0.40	0.18–0.28	0.16–0.24
Total K (%)	3.02–4.34	2.00–4.00	1.69–2.43	1.55–2.36
Total Ca (%)	1.41–2.08	0.50–1.00	0.42–0.62	0.48–0.72
Total Mg (%)	0.29–0.42	0.20–0.40	0.19–0.28	0.18–0.26
Total B (mg/kg)	–	5.0–20.0	–	–
Total Cu (mg/kg)	14–21	10–50	15–23	17–25
Total Mn (mg/kg)	110–143	20–80	51–81	23–37
Total Fe (mg/kg)	87–129	50–250	116–179	101–151
Total Zn (mg/kg)	25–36	10–50	15–22	30–46

Table 33.4 Nutrient sufficiency range of *Lagerstroemia* and Palms (Philip *et al* (2015)

Nutrients	*Lagerstroemia*	Palm—*Dypsis decaryi*	Palm—*Dypsis lutescens*	Palm—*Roystonea oleracea*	Palm—*Roystonea regia*
Total N (%)	1.25–2.50	1.63–1.96	1.17–1.68	1.31–1.73	1.21–1.86
Total P (%)	0.10–0.30	0.13–0.19	0.15–0.23	0.18–0.24	0.12–0.18
Total K (%)	0.50–2.00	0.45–0.71	0.54–0.82	0.53–0.78	0.57–0.99
Total Ca (%)	0.50–2.00	0.52–1.05	1.02–1.51	0.45–0.84	0.92–1.11
Total Mg (%)	0.10–0.40	0.07–0.15	0.08–0.14	0.13–0.19	0.14–0.20
Total B (mg/kg)	10–70	–	14–30	16–27	21–28
Total Cu (mg/kg)	10–60	8–13	14–22	9–13	10–15
Total Mn (mg/kg)	10–100	25–99	43–80	11–45	17–25
Total Fe (mg/kg)	100–300	92–109	85–125	108–156	167–233
Total Zn (mg/kg)	50–150	53–82	20–35	8–15	11–16

33.4.2.2 Palms (Dypsis and Roystonea sp)

Palms are grown in homes, parks, streets and commercial buildings as hedges, border plants and also as centre pieces and patio trees. They occupy pride of place along many avenues particularly along the East Coast Parkway, closer to Changi airport (Table 33.4).

33.4.3 Vegetables

33.4.3.1 Baicai, Xiao Baicai and Bayam (Philip *et al* 2015)

More than 80% of the leafy vegetables produced locally are derived from soil cultivation and the rest from hydroponics. Xiao baicai, Baicai, Bayam, Caixin, Kailan, Chinese cabbage, Kangkong, Lettuce and Mustard are the commonly cultivated leafy vegetables in the farms and community gardens in Singapore. Interest in edible gardening is gaining momentum and attracting a larger and younger group of participants. With the added thrust of building edible gardening capacity, more appropriate vegetables will be added to this list in future (Table 33.5).

A plant analysis report provides a snapshot of the nutrient level within the plant to help identify and address the issues of nutrient deficiencies, toxicities and imbalances (Schulte and Kelling 2016). Plant analysis can be interpreted by various methods. Experience with interpreting the overall plant analysis report is essential because of the many interacting factors which influence the concentration of any one element in plant tissue. Though various interpretation systems of the plant analysis result (Sumner 1979; Westermann 2005) have been used by the practitioners, the primary system compares analysis results with some pre-established norms such as critical value, sufficiency range or indexes/scores like the Diagnosis and Recommendation Integrated System (DRIS) (Beaufils 1973), Deviation from Optimum Percentage (DOP) (Montanes et al. 2008), Composition Nutritional Diagnosis (CND) indices (Ali 2018) and Plant Analysis with Standardised Score (PASS) (Baldock and Schulte 1993). Jones et al. (1990) had defined critical value as the concentration below which yields decrease or deficiency symptoms appear. Yield decreases before visible deficiency symptoms are observed for many nutrients.

Most advisory services use sufficiency ranges for primary interpretation of plant analysis results. Ratios and DRIS analysis are generally used as secondary and

Table 33.5 Nutrient sufficiency range of three vegetable crops

Nutrients	Baicai (*Brassica* spp.)	Xiao baicai (*Brassica rapa var chinensis*)	Bayam (*Amaranthus tricolor*)
Total N (%)	2.99–3.97	3.87–5.18	3.73–5.37
Total P (%)	0.55–0.70	0.52–0.73	0.59–0.87
Total K (%)	4.01–5.71	4.65–6.41	4.51–6.65
Total Ca (%)	0.82–0.87	1.54–2.46	1.50–2.17
Total Mg (%)	0.27–0.40	0.28–0.40	0.79–1.14
Total Cu (mg/kg)	14–20	13–18	14–22
Total Mn (mg/kg)	92–118	63–86	33–48
Total Fe (mg/kg)	1112–1485	209–253	180–267
Total Zn (mg/kg)	103–147	122–187	53–80

supportive evaluations (Campbell and Plank 2000). Comparing DRIS and nutrient sufficiency range in corn, Soltanpour et al. (1995) found sufficiency range to be superior to DRIS. Interpreters agree that both methods of interpretation have their advantages but seem to work best when used together (Mills and Jones Jr 1996). The sufficiency range that we developed for plants was obtained through surveillance results. As environment plays a major role in nutrient uptake and plant growth, these sufficiency ranges should be considered as general guides for recommendations for general horticulture and arboriculture in Singapore. However, apart from variation due to environmental effects, different plant species may have different critical levels. Ideally the sufficiency range is best worked out through field research but as with soils, there has been no specific research to establish any norms for plant nutrient sufficiency range in Singapore. Hence these set of values will serve as the first approximations for further work to refine the sufficiency range in future.

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34 Calcareous Oolitic Limestone Rockland Soils of the Bahamas: Some Physical, Chemical, and Fertility Characteristics

Robert W. Taylor and Lucy W. Ngatia

Abstract

Andros is considered the island in the Bahamas archipelago with the greatest potential for agriculture. However, very little has been published about the physical, chemical, and fertility characteristics of the soil although some areas in North Andros have been farmed intensively by commercial offshore farmers from the USA over the past 90 years. Having mainly pine vegetation, the land in the central part of North and Central Andros seems to be occupied, mainly by the immature aluminous lateritic rockland soils belonging to the San Andros soil series and varying in color from gray to reddish brown. This book chapter presents physical, chemical, and fertility information on some of the soils of North and Central Andros.

Keywords

Alkaline · Andros · Bahamas · Chemical · Oolitic limestone soil · Rockland soil

34.1 Introduction

Generally Bahamian soils are thin and discontinuous, mostly lack potassium and nitrogen, and therefore, exhibit low fertility (Foos and Bain 1995) but pockets of clay are also found throughout the landscape. The soils in Andros are developed from oolitic limestone, and oolitic soils are derived from dissolved calcium carbonate, which precipitate out as ooliths (Currie et al. 2019). Soils in Andros are usually sandy and poorly developed (Sealey 1985). The soil mainly exhibits low organic

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matter content and the pH is dominantly alkaline ranging from 7 to 8 as a result of being derived from limestone weathering (Currie et al. 2019; Henry 1974; Patterson and Stevenson 1977). The soils are young and reflective of the geologically young age of limestone parent material (Currie et al. 2019). The young soil exhibit dominance of stones and sand, and the smaller sized particles such as clay are lesser. The sandy soils commonly occur on unconsolidated carbonate sands and are composed of unaltered carbonate mineral and organic material (Foos and Bain 1995). The rockland landscapes are often rocky and flat and commonly have soft limestone substrate that is suitable for farming (Smith and Vankat 1992).

34.2 Soil Sampling

Composite soil samples were collected from farms and from the forests around the Bahamas Agriculture Research and Training Development Project (BARTAD) Area, the San Andros area, the Nicoll's Town area, and the Stanyard Creek area. The areas in Andros from where the soil samples were collected are given in Table 34.1. As indicated, both virgin forest and farm soils were sampled. The samples were air-dried, passed through a 2 mm sieve, and stored in metal containers and plastic bags prior to analysis (Fig. 34.1).

Table 34.1 Soil sampling areas in Andros

Soil #	Location
1	From around San Andros Airport—Farm soil—Didymus Smith
2	From around San Andros Airport—Forest soil
3	From BARC area—Light gray forest soil
4	From BARC pilot test farm—Wilfred Mackey
5	From BARC area—Forest soil—Near Wilfred Mackey
6	From BARC pilot test farm—Enoch Marshall
7	From BARC agronomy field 3-12A eastern Part
8	From BARC area—Forest soil near agronomy field 3-12A
9	From pothole behind North Andros high school
10	From Stanyard Creek—Light gray farm soil—H. Frazier
11	From Stanyard Creek—Light gray woodland soil
12	From Stanyard Creek—Gray farm soil—H. Frazier
13	From broadleaf Forest near Heastie's farm
14	From pot in which citrus grew—Soil came from Heastie's farm
15	From BARC agronomy field 3-12A legume fertility Trial
16	From BARC area—Reddish brown forest soil
17	From BARC pilot test farm—Ernest Ebanks
18	From Nicoll's town—Farm lot soil—Nemiah Wilson
19	From Nicoll's town—Beach ridge brown sand
20	From Nicol's town—Broadleaf, yellowish brown forest soil
21	From San Andros Airport area—Farm soil—Wendell Gaitor

Fig. 34.1 Map of the Andros Bahamas, the site where soils were collected

34.3 Soil Analysis

34.3.1 Physical Properties

Particle size analysis was performed using the hydrometer method as described in Alabama A&M University International Soils Bulletin #2 (Taylor et al. 2010a).

34.3.1.1 Soil Classification: Color and Texture

Color and texture classification of soils are provided in Table 34.2. The soils which developed from calcareous rock formed during the Pleistocene era and under pine vegetation have a variety of colors (Table 34.2). The three basic soil colors, however, are gray, brown, and red. Various gradations of these can be encountered in pockets

Table 34.2 Color and textural classification of the soils

Soil #	Soil color	% Sand	% Silt	% Clay	Soil texture
1	Grayish brown	55	29	16	Sandy loam
2	Grayish brown	47.7	24.5	27.8	Sandy clay loam
3	Light gray	54	27	19	Sandy loam
4	Light brown	58	24	18	Sandy loam
5	Light brown	53.3	24.9	21.8	Sandy clay loam
6	Brownish gray	48	31	21	Loam
7	Brownish gray	48	31	21	Loam
8	Yellowish brown	47.8	27.6	24.6	Sandy clay loam
9	Brownish red	4	24	72	Clay
10	Light gray	85	10	5	Loamy sand
11	Light gray	82	10	8	Loamy sand
12	Gray	82	13	5	Loamy sand
13	Dark gray	83	10	7	Loamy sand
14	Dark brown	83	11	6	Loamy sand
15	Brownish gray	55.3	26.3	18.4	Sandy loam
16	Reddish brown	25.7	44.1	30.2	Clay loam
17	Light gray	51.9	29.9	19.1	Sandy loam
18	Dark brown	64.4	25.8	9.8	Sandy loam
19	Brown	80.1	13.1	6.8	Loamy sand
20	Yellowish brown	19.5	29.5	51.0	Clay
21	Reddish brown	53.0	34.5	12.5	Sandy loam

and large basins in the pine forest. The brownish gray seems to be more widespread in North Andros being found, like the other soils, between and within the loose soft limestone rocks. The coastal sandy soils occupying the beach dunes are also used for agriculture in areas such as Nicoll's Town and Stanyard Creek. These soils may be light gray or brown. The predominant texture of the soils used in this study was sandy loam with all the coastal beach dune soils being loamy sands. There were a few sandy clay loams, one clay loam, and two clays (Table 34.2). The dominance of sand and less clay particle percentage is reflective of a young soil. The low clay content is known to limit soil water holding capacity (Currie et al. 2019).

34.3.2 Chemical Properties

The following chemical properties were measured using procedures outlined in the Florida A&M University International Soil Bulletin #1 (Taylor et al. 2017).

- Sodium bicarbonate extractable phosphorus (P)
- Langmuir P adsorption maximum
- Soil pH
- Electrical conductivity

- Exchangeable bases [calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na)]
- Cation exchange capacity (CEC)

34.3.2.1 Soil Phosphorus

The inorganic P in the Bahamian calcareous soil is dominantly fixed by calcium (Ca), whereby 55.7–99.9% was reported to be in the Ca-P fraction (Taylor and Woods 1981). Therefore, these soils will require heavy P fertilizer applications to adequately supply P to crops.

Soil P values given in Table 34.3 indicate that all the farm soils except samples No. 15 and 21 had either normal or high levels of available P measured by the sodium bicarbonate method. All the forest soils had low levels of available P. This indicates that newly cleared land would require heavy applications of P fertilizers or fertilizers containing P to attain sufficiency. Also, the frequent or long-term additions of P to these Rockland soils will result in a buildup of residual P and high fertility level. Previous study using sequential fractionation data illustrated that Ca and Mg

Table 34.3 Sodium bicarbonate extractable phosphorus (P) and Langmuir adsorption maximum

Soil #	0.5 M $NaHC0_3$-P level (range)[a] (mg/kg)	P adsorption maximum	
		mg/100 g	lbs/acre
1	133.6 (H)	42.5	850.0
2	13.2 (L)	60.0	1200.0
3	15.2 (L)	50.0	1000.0
4	110.4 (H)	–[b]	–[b]
5	10.4 (L)	40.0	800.0
6	66.4 (N)	47.6	952.0
7	68.4 (N)	49.0	980.0
8	12.0 (L)	66.6	1332.0
9	12.0 (L)	56.0	1120.0
10	38.4 (N)	59.0	1180.0
11	16.8 (L)	34.5	690.0
12	52.0 (N)	34.5	690.0
13	15.6 (L)	66.6	1332.0
14	148.0 (H)	32.3	646.0
15	33.0 (L)	44.0	880.0
16	10.8 (L)	100.0	2000.0
17	100.0 (H)	50.0	1000.0
18	36.0 (N)	60.0	1200.0
19	–[c]	–[c]	–[c]
20	14.8 (L)	50.0	1000.0
21	15.0 (L)	50.0	1000.0

[a](L) = low, (N) = normal, (H) = high
[b]Does not fit a Langmuir adsorption
[c]No measurement made
[d]mg/kg × 2 = lbs./acre

associated P accounted for proportionally more P in the agricultural soils; however, this fraction was below the detectable limit in non-agricultural soils. This suggests that repeated heavy application of phosphate fertilizer could have resulted in the formation of stable, crystalline calcium phosphate minerals in the agricultural calcareous soils (Zhang et al. 2014). It is reported that phosphate reacts with calcium carbonate in soil whereby it is fixed by calcium carbonate through precipitation and adsorption (Fixen et al. 1983; Zhou and Li 2001). Wandruszka (2006) further indicated that the role of calcium carbonate in P retention by calcareous soil is significant in the presence of relatively high P concentration, while the noncarbonate exhibit a more important role at lower P concentrations.

It is well documented that in calcareous soils, applied P fertilizers are adsorbed to the soil surfaces and are very slowly released to the soil solution. The rate of release can be too slow to replenish the soil solution with an adequate amount of P. The result for many crops may be P insufficiency and finally deficiency. However, it is possible to experimentally determine the maximum amount of P a given soil will adsorb per unit weight and adjust the quantity to pounds per acre. This is done by using the Langmuir adsorption equation (Olsen and Watanabe 1957) and calculating the absorption maximum. Woodruff and Kamprath (1965) reported that of the five soils they studied, the two with the highest adsorption maximum gave the highest yield for millet at ¼ the adsorption maximum and two with a lower adsorption maximum gave the highest yield at ½ the adsorption maximum, while the other with the lowest adsorption maximum gave the highest yield at the adsorption maximum. They concluded that soils with a high P adsorption maximum apparently are able to supply sufficient P for growth at a lower saturation than the soils with a low P adsorption maximum. The adsorption maxima of the soils in our study are generally higher than those of the soil in their study. Therefore, the assumption will be made that if the soils contain or are supplied with enough P to occupy ¼ the adsorption maxima, then P sufficiency can be acquired. The calculations to determine the quantity of P necessary to attain sufficiency are given in an earlier report (Taylor et al. 2010b).

34.3.2.2 Soil pH

Soil pH measurements were made in 0.01 M $CaCl_2$ following the procedure outlined in Florida A&M University International Soil Bulletin #1—Rev. 2 (Taylor et al. 2017). As indicated in Table 34.4, the pH of all the soils was in the slightly alkaline range except the red soil which had a pH of 6.6 (slightly acid) and is the only Bahamian soil the authors have measured which had a slightly acid soil reaction. This is good from a plant nutrition standpoint (Nelson 2003), but this red clay soil only occupied a very small area (a wide and deep pothole). The red aluminous lateritic soils of the Bahamas usually cover small areas and in the natural state may be slightly acid in reaction but would be expected to become neutral to slightly alkaline after cultivation due to release of calcium from the broken limestone rocks.

Table 34.4 pH, electrical conductivity (EC), exchangeable bases, and CEC of the soils

Soil	pH	EC[a] (mmhos/cm)	meq/100 g of soil (range[b]) Ca	Mg	K	Na	CEC[c]	Level
1	7.4	1.1	15.6 (H)	1.4 (H)	0.47 (N)	ND[d]	17.5	(H)
2	7.4	0.27	18.8 H)	0.56 (N)	0.15 (L)	0.07 (L)	19.6	(H)
3	7.5	0.70	19.4 (H)	1.1 (H)	0.33 (N)	ND	20.8	(H)
4	7.5	0.75	16.3 (H)	2.0 (H)	0.33 (N)	ND	18.6	(H)
5	7.5	0.40	24.5 (VH)	0.53 (N)	0.15 (L)	ND	25.2	(H)
6	7.5	1.1	15.4 (H)	1.2 (N)	0.70 (N)	ND	17.3	(H)
7	7.5	0.5	14.8 (H)	1.2 (N)	0.30 (N)	0.52 (N)	16.8	(H)
8	7.5	2.2	26.8 (VH)	3.3 (H)	0.48 (N)	2.55 (VH)	33.1	(VH)
9	6.6	0.50	18.0 (H)	1.4 (N)	0.62 (N)	ND	20.1	(H)
10	7.4	1.1	10.1 (H)	1.2 (N)	0.08 (VL)	ND	11.4	(N)
11	7.5	0.8	12.8 (H)	1.5 (N)	0.02 (VL)	ND	14.4	(N)
12	7.6	1.8	11.4 (H)	1.3 (N)	0.13 (L)	ND	12.8	(N)
13	7.5	0.54	20.3 (H)	0.77 (N)	0.06 (VL)	0.13 (L)	21.2	(H)
14	7.4	1.1	16.9 (N)	1.6 (N)	0.70 (N)	1.2 (H)	20.4	(H)
15	7.6	0.57	17.1 (H)	1.4 (N)	0.23 (N)	ND	18.7	(H)
16	7.1	0.73	20.1 (H)	0.33 (L)	0.26 (N)	ND	20.7	(H)
17	7.6	1.4	16.0 (H)	2.2 (H)	0.55 (N)	0.75	19.5	(H)
18	7.7	3.5	48.7 (VH)	7.1 (VH)	1.3 (H)	0.30 (N)	57.4	(VH)
19	7.6	1.7	15.4 (H)	2.1 (H)	0.21 (L)	ND	17.7	(H)
20	7.4	0.92	28.0 (VH)	2.4 (H)	0.61 (N)	ND	30.9	(VH)
21	7.5	0.84	16.0 (H)	1.1 (N)	0.23 (L)	ND	17.2	(H)

[a]EC = Electrical conductivity
[b](L) = low range; (N) = normal range; (H) = high range; V = very high range. The ranges are based on the small exchange approach to soil testing developed by Dr. Dale E. Baker, Department of Agronomy, The Pennsylvania State University
[c]CEC = Cation exchange capacity is a measure of the soils total capacity to hold positively charge nutrients
[d]Not detected

34.3.2.3 Electrical Conductivity

The electrical conductivity procedure used is outlined in Florida A&M University International Soil Bulletin #1—Rev. 2 (Taylor et al. 2017).

The electrical conductivity (EC) measurements of the saturated paste extracts of these soils indicate that only one soil (No. 18) would be a salinity hazard (Table 34.4).

34.3.2.4 Exchangeable Bases

Exchangeable bases were measured using the ammonium acetate extraction (pH 9) method (Taylor et al. 2017).

Levels of exchangeable bases (Ca, Mg, K, Na) are presented in Table 34.4. Most of the calcium values were high, with 4 of the 21 being very high. Generally, the exchangeable magnesium values were within the normal range with 7 in the high range and 1 in the very high range. Of the virgin forest soils, only one was within the low range. This could be interpreted to mean that newly cleared land should have adequate levels of magnesium for crop production. However, fertilizer additions of this nutrient may still be necessary after several croppings due to crop removal.

Most of the exchangeable potassium values were within the normal range. Three of the 21 values were very low and another five was low. Values for the virgin forest soils were all low. This strongly suggests that newly cropped land would have to be heavily fertilized with potassium containing fertilizers to have successful crop production.

The data also shows that the soils have the capacity to accumulate potassium for future crop production having been previously fertilized with this element since the farm soils generally had higher values than the adjacent virgin soils. Calculations for the amount of potassium to be added to reach sufficiency using exchangeable potassium values were presented in Alabama A&M International Soils Bulletin #3 (Taylor et al. 2010b).

Most of the soils have no exchangeable sodium with just one having a very high sodium value. It is very difficult to explain why some virgin soils have low levels of sodium, while most have no sodium. Sodium is not one of the essential plant nutrients but its presence in the soil in large quantities can cause structural problems and can also be an indicator of salt built-up (Vance et al. 2008; Warrence et al. 2003).

The cation exchange capacity (CEC) of the soils was determined by summation of Ca, Mg, K, Na as outlined in Florida A&M University International Soil Bulletin #1—Rev. 2 (Taylor et al. 2017).

34.3.2.5 Cation Exchange Capacity (CEC)

The cation exchange capacity (CEC) measurements were all in the normal to high range with two being in the very high range and most being in the high range. Based on the soil texture and the perceived low organic matter levels in the soils, these values were higher than expected. However, the type of clay minerals and the organic matter levels were not determined; therefore, one can only speculate. The problem of measuring accurate CEC levels in the Bahamian calcareous rockland soils was briefly discussed in Alabama A&M International Soils Bulletin #3 (Taylor et al. 2010b). Further research is needed to elucidate this problem so that one can with confidence measure and interpret CEC values and use them to aid crop production. The other question of the high exchangeable calcium was also discussed. More research is needed to also answer this question.

34.4 Conclusion

Andros soils are dominantly sandy in texture and slightly alkaline in pH. The alkalinity is a result of soil development from oolitic limestone. Therefore, the alkalinity could be a challenge to crop production unless the crops are adapted to content alkalinity. The sandy soils with low clay content are reflective of a young soil, the low clay content has potential to negatively affect water holding capacity. Forest noncultivated soils exhibited low P concentration compared to agricultural soils illustrating the influence of P fertilizer addition to availability of P. The soils exhibit high calcium concentration and normal potassium concentration. The CEC was normal to high; however, more studies are required on organic matter level and clay mineral content in order to understand CEC dynamics.

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Consequences of Anthropogenic Disturbance on Variation of Soil Properties and Food Security: An Asian Story

35

Nandini Roy, Ajay Kumar, Soumojit Majumder, and Prithusayak Mondal

Abstract

The degradation and destruction caused to our natural resources by the injudicious use of ecosystem services are rooted deep into the soil. Soil performs a wide diversity of functions those are essential for supporting and maintaining life forms on earth. Those vital functions include buffering and filtering fatal chemicals, contaminants and transformation of potentially harmful chemicals, maintaining proper structure, filtering the water, nourishing aboveground biodiversity, nutrient cycling and storing the carbon. It also acts as a base to support the interlinked ecosystem and therefore the food web, for instance, grassland, forest, marine. Therefore, a slight change in any of the physico-chemical properties of soil can set up a series of reactions over other ecosystems, threatening the sustainability of the functions. Asia being the largest continent in the world, supporting a huge population, has resulted in intensive utilization of its soil and other natural resources to fulfil its nutritional and livelihood requirements. The human interventions in various ways not only affect the soil health directly, but also

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influence on the soil functioning and plant's physiological aspects indirectly through climate change. In Asian context, the most alarming conditions affecting the soil health and productivity include soil erosion, compaction, sealing, waterlogging, change in soil carbon, soil contamination by heavy metals, soil acidification, soil salinization, sodification, loss of biodiversity and nutrient imbalance. These problems are mainly due to industrialization, constructions and intensive cultivation to meet the increasing demand for food. Increase in temperature as a result of global warming has resulted in acceleration of soil reactions adding up to the problems of increased release of carbon dioxide causing variations in carbon content, structure, water holding capacity, nutrient content and stability of soil. Therefore, to eradicate malnutrition and ensure food security in a densely populated country like Asia, it is a priority to create awareness among the population about the sustainable use of resources including soil. Policies enabling identification, reclamation and proper management can be the key to ensure protection of soil health.

Keywords

Soil health · Ecosystem · Population · Food security · Natural resources

35.1 Introduction

Soil is one of the major constituents of growth and developments of living organisms, agricultural productivity or fresh produces, and also acts as pillar for the rapid urbanization and industrialization. The soil aggregates, which originate from faunal root and microbial activity, act as a reservoir of carbon and help the soil to maintain its production capacity to sustain the global needs (Six et al. 2004). However, formation of soil is a cumbersome process, leaded by interaction between various biotic and abiotic factors (Balasubramanian 2017).

Due to the human intervention in a large scale, the balance between the physical, chemical and biological entities of the soil ecosystem is hampered which eventually leads to degradation in soil quality and results in less productivity. The human activities that mine the natural resources in an intensive manner may lead to direct and indirect long-term consequences. Soil is the provider of all the macro- and micronutrients that are essential for plant growth. Changes in land use pattern, increasing deforestation for rapid industrial and agricultural growth have led to degradation in the soil health and resulted in loss of the valuable topsoil that supports the healthy crop growth. Therefore, this phenomenon can be implied as a two way process. This is because, on the one hand, utilization of natural resources in an unsustainable manner, dumping the toxic outputs into the soil and water bodies as well as in the atmosphere as a release of harmful gases not only affects the surrounding environments, plant and soil productivity but also the health of human beings. In a long run, it is causing unprecedented change in climatic conditions altering physiological functioning of crops, reducing the yield and threatening the food security (Wang et al. 2018). The significance of climate change affecting the food security lies in the fact that all other factors remaining optimum, climate and crop cultivar can play a major role in altering the maximum potential yield. Climatic variability can explain about 60% of the yield variability influencing the production as well as farmer's livelihood (Ray et al. 2015). Therefore, the relationship between climate change and yield gap has been studied extensively by scientists (Sinha and Swaminathan 1991; Saseendran et al. 2000; Aggarwal and Sinha 1993; Rao and Sinha 1994).

According to the recent trends, the temperature and precipitation have changed both locally and globally. Over the centuries, the temperature has increased by several degrees owing to both terrestrial and extra-terrestrial activities. In the last century, the global mean temperature has risen by almost over 15 °C. It is apparently more due to anthropogenic activities, which was measurable by the facts that more greenhouse gases were emitted from industrial areas and from burning of fossil fuels than from the forest areas, higher outpouring of methane and nitrogen oxides from intensively cultivated agricultural lands (Karmakar et al. 2015). Separate causes can be attributed to the various alterations in soil properties like deterioration of soil quality, soil erosion, heavy metal contamination, less stability of the soil as an indirect effect of variations in temperature and precipitation that governs the rate of decomposition of organic matter (Tao et al. 2003; Arias et al. 2005; Moebius et al. 2007; Reynolds et al. 2009). Nevertheless, a collective and comprehensive study is need of the hour to determine the substantial cause.

The Asian Soil Partnership includes three segments–South Asia (eight countries: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka), East Asia (five countries: China, Democratic People's Republic of Korea, Japan, Mongolia and Republic of Korea) and South-East Asia (11 countries: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Myanmar, Malaysia, Philippines, Singapore, Timor Leste, Thailand and Viet Nam) (FAO 2015). The Asian continent is mainly located in eastern and northern hemispheres and is the largest on earth comprising about 16% of its land area. It is also the most populous continent consisting of almost 55% of the world's population with the population density on an average 1.87 person per hectare as compared to the world (0.54 person per hectare) (FAO 2015). Asia enjoys the privilege of warm and humid climate with rich natural resources. Availability of abundant lowland areas and monsoon type of climate enabled the Asian countries to meet the nutritional requirements of its vast population (Kyuma 2004). Rapid changes in the productivity due to human disturbances and the change in the climatic pattern have raised an alarming situation regarding the food security of Asian countries (Wang et al. 2017). Asia is facing rapid changes in terms of natural resources and socio-economic factors due to variation in land use patterns. Even an increase in temperature from 1.5 to 2 °C in South Asia can trigger melting of glaciers; rainfall variability can reduce the availability of irrigation water, threatening the food security to a large extent (Vinke et al. 2017). The summary of consequences of this situation could be less production, high market price, which will affect livelihood of millions of Asian people (Shankar et al. 2019; Wang et al. 2017; Aryal et al. 2019). In South Asia, agriculture generates employment for 60% of the labour force, serves as the source of livelihood generation for 70% of the people and contributes about 22% of the gross GDP (Wang et al. 2017). Therefore, the adaptation measures for the unprecedented climatic conditions and the management strategies for the degraded lands are of utmost importance in the present context. It is also the foremost requirement, to understand the different functions performed by the soil to receive a lucid image of how it supports our existence.

35.2 Significance of Material and Energy Transportation into the Soil by Natural and Socio-Economic Processes

We all are aware that soil is not a living entity. Nevertheless, it possesses the properties that are quite similar to the living system. This is mainly because of the vast biological lives it holds and the nutrient pool that supports it. Soils are naturally embedded in Odum terrestrial ecosystems. Soil includes biotic (plant roots and microorganisms) and abiotic components, water and gaseous compartments, the functions it performs through a number of interactions (e.g. trophic networks, mineral weathering, decomposition, humification) and its visible upper and lower limits (from surface soil to parent rock). Therefore, soil is indeed an ecosystem (Ashby and Pfeiffer 1956).

The most dangerous myopic perspective inherited by the mankind was promulgated clearly by Marbut (1921): ‘Probably more harm has been done to the science by the almost universal attempt to look upon the soil merely as a producer of crops rather than as a natural body worthy in and for itself of all the study that can be devoted to it, than most men realize. The science has undoubtedly been retarded in its development by this attitude’.

Functions of a soil as an Ecosystem Supporter and its socio-economic significance: (1) Soil delivers goods and services to mankind like biomass for food, fodder, renewable energy; (2) It filters and dilutes the toxic wastes dumped on it as well as noxious chemicals discharged into the water bodies; (3) It buffers the atmosphere; (4) It acts as a seat of carbon sequestration by reducing the atmospheric carbon dioxide resulting in increase of plant mass production and decomposition of residues present in the soil; (5) It maintains a diversity of organisms, and nurtures biodiversity; (5) It supplies clean water for agriculture and for household or manufacturing purposes; (6) It stores the atmospheric heat, playing a vital role in heat regulation.

Soil functions were categorized into five categories by Blum (1988)—two of which were labelled as ‘socio-economic’ and ‘technical-industrial’, respectively, the other three were termed as ‘ecological’. The soil functions can simply be defined as the uses of soil by human population as well as more generally by animals and plants (Baveye et al. 2016).

The First Category (Socio-Economic Functions) It includes the supply of clean water and other kind of raw materials like sand, gravel, clay, coal which are mainly used for buildings, manufacturing or construction purposes. Over the millenniums, clay is used to make houses which is relevant even today if we take into account the amount of burnt bricks that are used (Staubach 2005).

The Second Category (Technical-Industrial Functions) Soil provides a platform for all type of construction works. So it acts as a structural support to the buildings and roads.

The Third Category (Ecological Functions) The following functions involve biomass production, for instance, production of crop in agricultural fields and trees in forests. Soil serves as a support for roots, and acts as a provider of nutrition, air and water for plant growth.

The Fourth Category (Ecological Functions) It refers to the filtering and buffering capacity of soil like the biological and chemical components that are dumped into the soil. Soil plays an interface in the water cycle where it physically acts as a filtration agent, fostering breakdown of biological or biochemical transformation of toxic compounds.

The Fifth Category (Ecological Functions) It involves the soil's capability to preserve genes that is useful for the human population. It also includes the preservation of archaeological and paleontological remnants that tells a lot about our civilization. This category also includes soil's capacity to store the organic carbon and aid in maintenance of soil health.

Although the function performed by the soil largely depends on the management or the change in land use. For example, a farmer's decision of changing a pasture land to a crop field (Renison et al. 2010) or converting industrial land to crop field. This particular change in management is interrelated to other functional components as well, like recharge of groundwater or filtration of toxins.

The most important aspect of the soil system is its resilience or the capacity to revert back and attain a balance between its functions under anthropogenic interventions. Humans need to realize the potential that the soil holds in performing these functions and to the extent in which it can perform those functions. Soil can be seen as a phase where other spheres interlink themselves, i.e., atmosphere, biosphere, hydrosphere and lithosphere (Karmakar et al. 2015). Therefore, the pedosphere plays a pivotal role in regulating the chain of reactions or variations related to the other spheres. So, a disturbance in balance between any of the components can create a series of reactions from one ecosystem to other. Prolonged imbalance can stand as a potential threat to the inhabitants and the planet as a whole (Fig. 35.1).

The environmental concerns that are relevant even in the modern day were distinctly illustrated by Rachel Carson in 'Silent Spring' back in 1962, where he described about the ill effects of widely used pesticide DDT (dichloro-diphenyl-trichloroethane). This pesticide, being used in huge quantities among farmers,

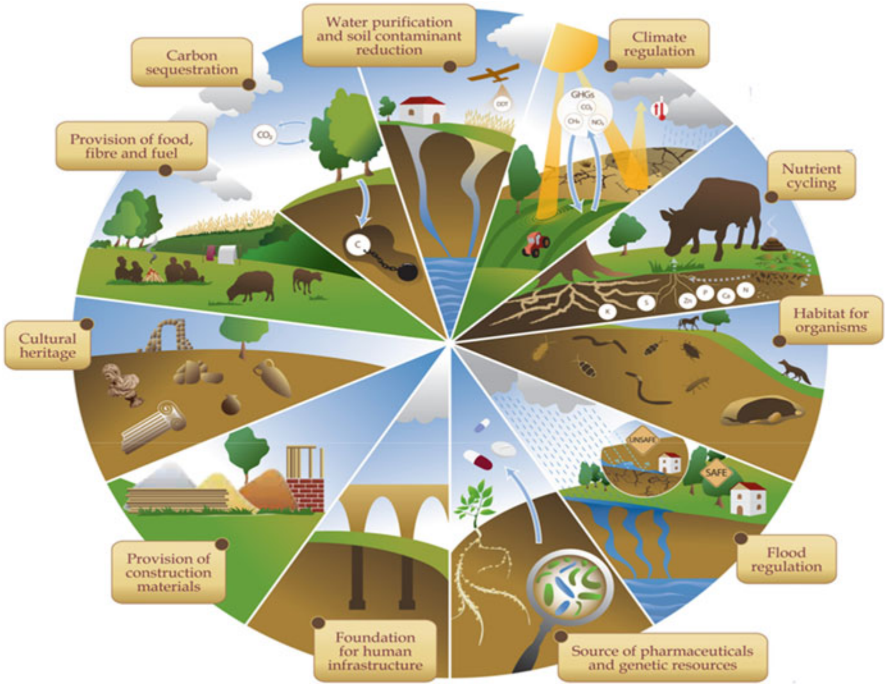

Fig. 35.1 Schematic diagram of soil functions with the subtitle 'Soils deliver ecosystem services that enable life on earth' which was adapted from FAO website by Baveye and his co-workers (Baveye et al. 2016)

entered the food chain and resulted in bio-accumulation, causing cancer and damage to genes (Saha et al. 2017).

35.3 A Brief Account of Some Anthropogenic Disturbances and the Intensity of Their Effects in Asian Subcontinents

35.3.1 Common Land Use Practices That Affect the Soil System

35.3.1.1 Farming

Continuous tillage and intensive utilization of soil for the purpose of growing crops renders the soil loose and it becomes prone to erosion. The problem of decreased soil fertility is worsened further by uncontrollable use of inorganic fertilizers and plant protection chemicals.

35.3.1.2 Overgrazing

Overgrazing leads to significant reduction in vegetation covering the surface. Therefore, the soil surface becomes unprotected and prone to erosion. The fertile top soil can be easily carried away by wind and water.

35.3.1.3 Construction

Construction of buildings, bridges, dams and other concrete structures creates profound effects on surrounding ecosystems. It often disrupts the food chain and creates an imbalance between various ecosystems.

35.3.1.4 Mining

Deposition of acidic or alkaline chemical compounds which are essential for the extraction of various metals results in change of pH and therefore adversely affecting the sustenance of microorganisms in soil.

These human activities are practised intensively for agricultural and industrial purposes causing havoc on soil physical chemical and biological properties which gives origin to problematic conditions in soil like wind erosion, water erosion, soil acidification, soil sodification, compaction, water logging, loss in soil organic carbon, heavy metal contamination. So, we can get a notion that even if some targets are fulfilled in achieving access to basic necessities, there exists an ever-emerging threat in sustainable resource management.

The subsisting conditions in Asia can jeopardize the rapid development in terms of economic growth. Keeping in sight the insatiable demand for the natural resources for rapid industrialization, we may soon start running out of the ecosystem services with exponential rise of greenhouse gases in our atmosphere, resulting in pollution and life-threatening diseases in human beings (ESCAP 2018). As Asian countries mostly have a huge population, the amount of generation of municipal and industrial wastes are also soaring day by day with nearly negligible attempt of terrestrial ecosystem management.

35.3.2 Some Highlighted Points in Relation to Energy Consumption in Asian Countries

- The resource intensity of domestic material consumption of low-income countries is about 11 times higher than that of the high-income countries (UNESCAP 2018).
- From 1990 to 2014, energy demands of this region have doubled in terms of fossil fuel use. The trends may outgrow any renewable energy re-growth (UNESCAP 2018).
- As far as, freshwater withdrawal is concerned, agriculture stands as the sector that can be largely taken into account. Although a slight shift can be visualized due to growing urbanization. More than 90% of the water was withdrawn for agricultural purposes in 13 countries of this region (FAO 2017a, b). It can also be estimated that climate change may trigger unavailability in freshwater at low

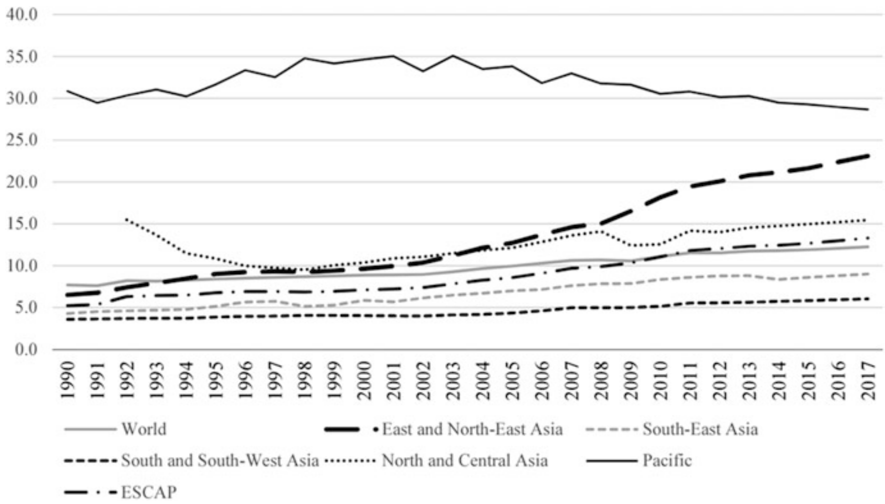

Fig. 35.2 Trends in domestic material consumption, 1990–2017 (Tons per capita) (Source: ESCAP calculations based on data from the ESCAP Statistical Online Database (ESCAP 2018)

latitudes and especially in those countries where crop fields are heavily irrigated, like India and China.

- 29 out of 48 countries in this region in 2016 are depicted as water insecure due to the scarcity of water and injudicious use of groundwater. Asian continent is in the seventh rank out of 15 world's biggest continents in utilizing groundwater resources unsustainably. Moreover, research suggests that the use will increase by 2050 (ADB-IADB 2014).
- Urbanization has to be done in expense of existing natural resources in that region. Therefore, the diagrams representing resource use are proportional to the urbanization in that region, which is understandable from the Figs. 35.2, 35.3 and 35.4. Therefore, the urgent situation demands the kind of infrastructure that is resource efficient and plans to optimize the development in whatever space available for the purpose. Only then, the purpose of maintaining a balance between creating wealth and protecting the natural resources can be carried out competently. East Asia and China showed increase in resource consumption, along with India, however, less drastic changes were observed in Indonesia and Thailand (ADB-IADB 2014).
- In the Asian countries, agriculture and allied sectors are the potential sectors for draining out the resources. The rising demand for food, feed, energy and raw materials to fulfil the needs of a huge population is putting a huge burden on land and water (FAO 2017a, b).

The figures below represent the resource consumption of Asia in diagrammatic forms (Figs. 35.2, 35.3 and 35.4).

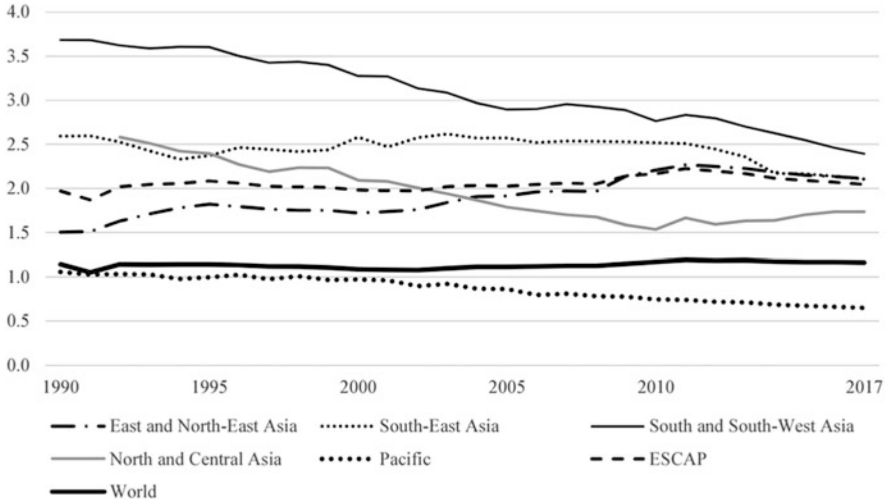

Fig. 35.3 Trends in resource intensity: domestic material consumption, 1990–2017 (Kilograms per United States dollar) (Source: ESCAP calculations based on data from the ESCAP Statistical Online Database using 2010 gross domestic product (GDP) (ESCAP 2018)

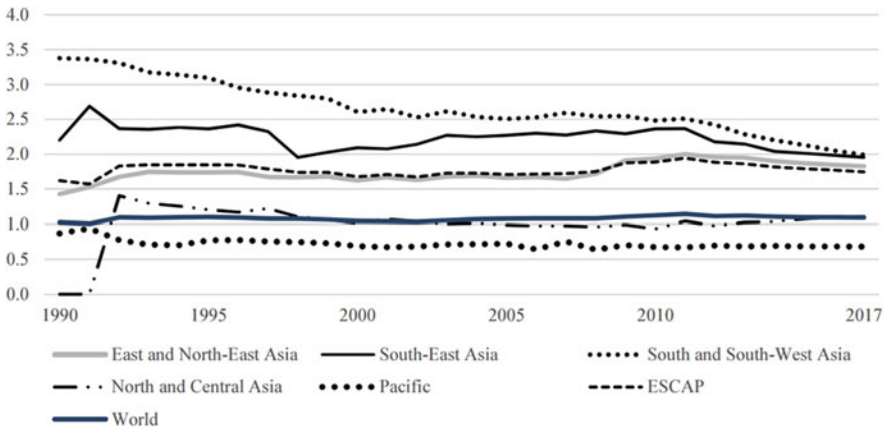

Fig. 35.4 Trends in resource intensity: material footprint, 1990–2017 (kilograms per United States dollar) (Source: ESCAP calculations based on data from the ESCAP Statistical Online Database using 2010 GDP) (ESCAP 2018)

35.3.3 Emerging Threats to Ecosystem and Biodiversity

In spite of the fact that coastal ecosystem renders a number of services and benefits, there have been drastic reduction in the mangrove cover in the Asian coastal region in the period of 2002–2012, which was captured by the satellite imagery (Asa and Susan 2015). If the current trend continues, the ecosystem services provided by the mangrove forest will vanish by 2050 that will be worth of $2.2 billion on an annual basis (Brander et al. 2012).

The International Union for the Conservation of Nature and Natural Resources (IUCN) Red List of Threatened Species, which covers critically endangered, endangered and vulnerable plants and animals, revealed that the flora and fauna of the region are threatened with extinction. In the tropical zones of South and South-East Asia and the Pacific all the sub-regions have shown a decline in Red list Index with an alarming risk of biodiversity loss (Statistical Yearbook for Asia and the Pacific 2016). Between 2000 and 2015, approximately 135,333 square kilometres of forest area was lost in this region. South-East Asia lost approximately 158,862 square kilometres of natural forest area within the same period (ESCAP-ADB-UNDP 2017). The reason can be attributed to the large-scale increase in timber extraction, bio-fuel plantations, export market for palm oil and intensive agriculture.

35.3.4 Pollution

Plastic and the related toxins enter into the food chain by accumulating in the body of organisms and enter the human body resulting in outbreak of fatal diseases. Plastic is the most prevalent litter in case of marine and soil ecosystems. Over 80% of marine plastic waste is generated from land-based sources. 75% of the leakage from land based is due to the uncollected waste, and the remaining 25% is from the waste management system (Geyer et al. 2017).

In the Asian cities the accumulation of food waste is even higher than the European countries (Nord and Lynch 2009). In South and South-East Asia, where rice is the dominant crop, a considerable amount is lost during post-harvest handling, processing and storage. Another 40% food loss occurs in the hands of retailers and consumers (Brinkman and Sombroek 1996; Brinkman and Brammer 1990). Use of inefficient technologies and intensive energy consumption patterns, both domestically and industrially, has led to emission of air pollutants and particulate matter, degrading the air quality. According to the latest estimates in 2015, Western Asia and Central and Southern Asia were affected by the highest concentrations of particulate matter with measurement of 2.5 micrometres or less in diameter (Harnos and Csete 2008).

35.4 Inter-Linkage of Human Activities with Soil Properties

The discussion till now revolved around the collective harm that the unsustainable human demands are imputing to the ecosystem, which is disrupting the functions that they provide and thereby hitting the economic gains derived from the services. Soil properties can be classified into physical, chemical and biological. The amalgamation of the properties and the balance between them make soil a functional ecosystem. When the exogenous activities congregate with the climatic variability, the degradation process is further enhanced. Therefore, a profound understanding is essential about the inter-relationship between the soil properties and the intervening activities.

35.4.1 Effect on Physical Properties

Human activities cause depletion in soil, air and water, result in destruction of soil structure making the soil prone to erosion by wind and water. Continuous intensive agricultural practices also lead to soil compaction rendering the soil impermeable to root development.

35.4.1.1 Soil Erosion

In humid regions like East and South-east Asia, due to torrential rainfall, soil is even more prone to eroding forces. This process is further aggravated by the climatic variability in the region having alternating dry and wet seasons, whereas wind is the functional agent of erosion in drier regions (FAO 2015).

Soil erosion by water is mainly dependent on the intensity of rainfall, erodibility, management practices and the topography of the region. Generally, bare lands with inadequate surface cover are highly prone to soil loss by the erosion. In Asian countries, annual soil losses from paddy field were estimated to be lower than 1 tonnes ha^{-1} (Chen et al. 2012; Choi et al. 2012). In South Korea, where no conservation practices are followed soil loss from upland crop areas on slopes was 38 million tonnes ha^{-1}, which is quite higher than the low lands (Jung et al. 2005). Therefore, it is certain that forests and paddy fields will have a lower intensity of water erosion than the barren and sparsely vegetated areas. Geographical characteristics and patterns of land use generally govern limits or variations in soil erodibility. Forests are generally located on higher slopes than the cropland. Therefore, in some point of time the forest land must have been exposed to erosion, which may be the reason behind upland crop and forest soils mostly having greater fractions of particles having less erodibility, i.e. silt and clay (ESCAP 2018). The paddy fields located at the lowlands are having more erodible fractions. However, the soil in the paddy fields is protected from rainfall because of its submerged condition and the ridges that somewhat obstruct the running water (Chen et al. 2012; Choi et al. 2012). It is also observed that well-managed grasslands and forests have lower levels of erosion (Kitahara et al. 2000).

35.4.1.2 Compaction

Compaction results in decrease of porosity, hydraulic conductivity and air permeability, which leads to deterioration of physical characteristics and productivity of soil. Heavy mechanization with long-term conventional tillage practices is the root cause of compaction in surface soil or sub-soil. However, slightly compacted soil may be conducive to productivity due to less chances of erosion.

In India, studies on rice–wheat cropping system revealed that over a period of time there was increase in bulk density of the sub-surface soil indicating compaction. The reason may be due to the use of heavy machineries along with puddling (Sidhu et al. 2014; Singh et al. 2009) Experiments suggest that, in order to increase the yield, heavy mechanization in conjunction with increased cultivation is the main cause of compaction for Asian countries (Zhang et al. 2006). The compacted soil also resists penetration, hence aggravating the runoff problem. Consequently, the toxic wastes and metal contaminants are unable to be filtered by the soil and ultimately pollute the water bodies. Heavy grazing and trampling have also led to severe soil degradation and compaction in pastoral steppes of Mongolia and Inner Mongolia of China (Kruemmelbein et al. 2008). In urban areas, compaction generally occurs due to human traffic and vehicles which cause serious damage to plant roots, as root density is mostly concentrated in the upper 50 cm of soil layer (Millward et al. 2011).

35.4.1.3 Sealing

The sealing process, which is essential for construction of road and buildings, affects the significant soil properties in the surface soil and sub-surface soil region in the process of excavation and deposition of construction materials. In Japan, for the purpose of land-levelling huge volumes of soil are excavated and deposited in other regions (FAO 2015). Sealing is done to enhance the physical strength of the soil and lime is often added to increase the strength of base of a road which makes the soil alkaline (Jim 1998). Asia has the largest impervious surface area (ISA) ratio mainly due to the fast growing urban areas. According to several researches, the countries with increasing sequence of ISA are China, India, Indonesia, Japan and Bangladesh (Elvidge et al. 2007). Rise in ISA is generally related with environmental issues like increase in surface water runoff (Booth 1991) and less carbon sequestration (Milesi et al. 2003).

35.4.1.4 Waterlogging

It can occur mainly in two categories: one is in marsh lands in which permanent waterlogging may occur, another one is intermittent waterlogging in areas that are prone to flooding and along the coastal regions. Other human intervened causes can be associated with waterlogging like poor drainage systems, development of industries and deforestation. All these reasons can play a vital role in waterlogging as all these activities increase soil compaction considerably. In Asia, around 4.6 million ha area is affected by waterlogging which includes the irrigated areas of India and Pakistan, according to an international estimate—The Global Assessment of Soil Degradation (GLASOD) made by the International Soils Research and Information Centre (ISRIC) under the aegis of United Nations Environment Programme (UNEP). Waterlogging is also a grave reason behind salinization. Since the time when irrigation schemes started in Asian countries, i.e. 1930, the water table lying beneath the irrigated areas was monitored (Ahmad and Kutcher 1992). The waterlogged area in India was more than twice the GLASOD estimates, according to the monitoring results (FAO 2015).

35.4.2 Effect on Chemical Properties

35.4.2.1 Soil Organic Carbon Change

Data shows that due to retention of soil organic carbon (SOC) there was increase in crop yield in East and Southeast Asia. SOC also accumulates in forest areas. SOC is decreasing in South Asia because of the usage of crop residues mainly as fuel and fodder. Therefore enough residues are not returned to the soil. In Indonesia, mainly three factors come into play those regulate the SOC both in cropland and in forest-intensive conventional cultivation, deforestation and inefficient managements of land. Degradation of grassland is also a major cause for losses of SOC stock (FAO 2015).

Three methods to estimate soil organic carbon change from 1990–2009 were compared by Piao et al. (2012) in five East Asian countries. The remote sensing model approach concluded that the sub-region had the net ecosystem carbon sink (+0.293 Pg C year^{-1}). They also yielded the result that there was net SOC increase (in Pg C year^{-1}) in forest (+0.014), shrub (+0.022), cropland (+0.022) and SOC decrease in the grassland (−0.003).

An artificial neural network model was developed to link SOC change to six different parameters—soil type, land use type, latitude, longitude, elevation and original SOC in 1980.According to Yu et al. (2009) in Chinese croplands there was approximately increase of 260 Tg C between the period 1980 and 2000 in the top soils of 0–20 cm depth. The reason behind it can be increase in crop yield and retention of residues. But it was also clearly visible from other experiments that grasslands have less retention capacity of SOC than that of forests. In China, at least 5.29 million ha grassland had degraded between 1986 and 1999 (Han and Gao 2005). The estimates of carbon sequestration ranged from 234 to 304 Tg SOC in between the period of 1980 to 2000 on the area of 249.32 million ha which may be due to forest expansion and re-growth (Zhou et al. 2006; Xie et al. 2007). The total SOC storage estimates in China showed a wide range of variance in 0–100 cm soil layer, i.e. from 50 to 183 Pg (Xie et al. 2007). The approximate areas and corresponding carbon stocks are as follows: paddy growing land—29.87 million ha and 2.91 Pg C, uplands—125.89 million ha and 10.07 Pg C, forest—249.32 million ha and 34.23 Pg C, and grassland soils—278.51 million ha and 37.71 Pg C (Xie et al. 2014).

35.4.2.2 Soil Contamination

Various activities in most Asian countries are responsible for contamination of cultivated lands, like mining, smelting, intensive use of agrochemicals, application of sewage and sludge and uses of animal manures (Luo et al. 2009). Presence of high concentration of arsenic (As) in groundwater poses a potential threat to agriculture (Brammer and Ravenscroft 2009) which is further magnified due to mining, like in the case of southern Thailand (Williams et al. 1996). Rice fields in Guandu Plain in Taiwan, Province of China, are heavily contaminated with arsenic (As) and lead (Pb) (Zhuang et al. 2009; Chang et al. 1999). In Thailand, Cadmium (Cd) poisoning was found under paddy fields in zinc (Zn)-mineralized areas (Simmons et al. 2005).

Therefore, it is the need of the hour to reduce the hazardous concentration of Cd, As, Pb, Zn and Cu, as it can cause serious threat to human health. Especially in case of rice, due to its requirement of large quantity of water and anaerobic conditions, As is present in trivalent form which is readily absorbed by plants (Brammer and Ravenscroft 2009).

The Agricultural Land Soil Pollution Prevention Law (ALSCPL) in Japan has limited the Cd concentration in rice grains produced in field and not the Cd concentration in soil of the field. The main reason behind this is because bioavailable Cd in soil is greatly affected by the management practices undergone for paddy cultivation (Asami 1981). In Chine due to rapid industrialization, urbanization and intensive agriculture, about 19.4% of arable land is facing high levels of Cd, Nickel (Ni) and As pollution. Soil contamination has also hampered 107 tonnes of food supply annually (Wei and Chen 2001).

35.4.2.3 Soil Acidification

Acid sulphate soils are widely prevalent in coastal plains of Southeast Asia and southern China. The total area in Southeast Asia that is covered by acid sulphate soils is 7.5 million hectares (Shamshuddin et al. 2014). These types of soils also show sensitivity to external acid deposition (Hicks et al. 2008). About one-third of the Vietnam is covered with ferralitic, basaltic, and grey degraded soils, which show potentiality for acidification (NISF 2012). Unbalanced and intensive application of chemical fertilizers is the reason that can be attributed to the soil acidification in Vietnam. Data derived from International Fertilizers Association (IFA) demonstrated that from 1961 to 2012, the use of NPK fertilizers increased by 31 times (IFA 2012). The increase in fertilizer consumption and its unbalanced use have resulted in development of acidity in soil solutions. A certain type of fertilizers including organic can even add to the problem of acidity (Nguyen 2014). The presence of sulphate soils is another reason that can be attributed to the problem of acidification. Soil acidity can be managed using some cost-effective technologies like selection of acid tolerant crops, liming, application of organic matter and balanced fertilization. But application of acidic fertilizers like ammonium sulphate may increase the problem (Kamprath 1984). The total area of acid soil in China is approximately 204 million ha which is mainly distributed in tropical and subtropical regions south of the Yangtze River. The uncontrolled application of ammonium-based fertilizers have led to acid decomposition and have increased the soil acidification in China over the past three decades. Soil pH has decreased by 0.23 units for cereal crop fields and 0.30 units for cash crop fields in between 1980 and 2000 (Guo et al. 2010). It was mainly due to use of acid based fertilizers like ammonium sulphate, but deposition of acids were mainly responsible for acidity in forests. Excess application of ammonium fertilizer and insufficient leaching is likely to be responsible for salinization and acidification of vegetable greenhouses (Guo et al. 2010).

35.4.2.4 Soil Salinization and Sodification

Salt-affected soils are widely distributed in semiarid and arid zones of central and west Asia. It is also seen to be developing in certain coastal areas mainly by intrusion of salt water in South and Southeast Asia. According to the GLASOD study, even the dry region is estimated to have 42 million ha affected due to salinization. Approximately 4 million hectare in dryland is included in India and Pakistan. Salinization is also a marked problem in irrigated area and almost 10% of the irrigated area in India is affected by salinization, according to the GLASOD estimates. Particularly for lowland rice production, salinization can be a major problem. According to the GLASOD estimates, there are certain areas that are strongly affected by salinization and are therefore abandoned. But differences were observed between the GLASOD estimates and countries' own estimates, indicating to the fact that some areas were natural saline soils. The value of India ranges between 7 and 26 million ha which is much higher than the GLASOD estimates of 4 million hectares. The tide lands that have gone through reclamation also stand unsuitable for growing crops due to certain constraints like soil salinity, higher level of water table along with poor drainage. Capillary rise of saline groundwater and evapotranspiration during the dry periods generally lead to salinization of surface soil. The reclaimed tidelands with high salinity can be managed by controlling the quality and amount of irrigation water (Jung et al. 2002). As the desalinization process progresses the characteristics of reclaimed soil changes like its chemical properties, weak physical properties, destruction of soil structure causing waterlogging and altogether it hinders the crop growth (Park et al. 2011).

35.4.3 Effect on Soil Biological Properties

35.4.3.1 Loss of Soil Biodiversity

In China the converted land from agriculture, forest and grassland between 1996 and 2008 are estimated 1475×10^4 ha, 269×10^4 ha, and 536×10^4 ha, respectively (Wang et al. 2012). Therefore, it is obvious that the eminent factor behind biodiversity loss is the change in land use pattern. But there were attempts in specific countries to restore the biodiversity loss, for instance, in the coastal lands in the Jiangsu Province of China. Higher diversity of macrofauna is often observed in uncultivated lands or forest areas than the land under continuous cultivation (Baoming et al. 2014). The faunal diversity of a particular area is highly correlated with vegetation and macrofaunal distribution (Baoming et al. 2014). A study on soil microbial communities of an Acacia tree plantation established on degraded land in Thailand revealed that there was a reduction in microbial communities in comparison with forests (Doi and Ranamukhaarachchi 2013).

Studies in India also indicated the similar results of reduction in microbial population. Increase in population has shown adverse effects on Nilgiri biosphere reserve in the Western Ghats of India, which is a global biodiversity hotspot (Mujeeb Rahman et al. 2012). Although land management in this area has shown considerable effect on soil macrofauna and obvious response of macro-invertebrates to land use changes (Rossi and Blanchart 2005), but there was a high similarity between the macrofauna present in undisturbed forest areas and disturbed forest lands, which indicates the resilience capacity of the soil. Soils were collected from 15 different land use sites and its morphological analysis of soil vertebrates suggested that vast range of faunal groups were present in the samples including earthworms, ants, termites, grasshoppers, crickets, centipedes, millipedes, spiders (Mujeeb Rahman et al. 2012). Therefore, from these studies it was quite clear that forest soils are more enriched in terms of taxonomy and family than the soils under cropping system and plantations. A diversity of microorganisms, ants and termites were in areas with least human activities and the number increases with more complex ecosystem of forests. The number of earworm species doubled in the forest areas as compared to pasturelands (Blanchart and Julka 1997).

A comprehensive analysis of threats on soil biodiversity in Asia is not done properly due to few following reasons like lack of research and information, vast diversity of organisms and size of organisms. A new technology has been developed using the complex systems and computer technology which made it possible for the tools of statistical physics to assess the condition of farmland soil (Yokoyama 1993). Cultivated lands undergoing proper management practices like use of organic fertilizers, crop rotation were able to maintain the required microbial population. Intensive cultivation practices like monoculture, intensive tillage, excessive use of chemical fertilizers and soil contamination from uncontrolled use of agrochemicals for pathogen and weed control have led to subsequent deduction in microbial population of soil.

35.4.4 Effect on Soil Fertility

35.4.4.1 Nutrient Imbalance

Optimum and balanced use of fertilizers or nutrients may be helpful to increase the yield of crops, whereas uncontrolled inputs of nutrients may destroy the balance of the ecosystems and may stand as a potential threat to human well-being. Nutrient losses mainly occur in the gaseous form through emission into the air, or are discharged into water bodies through leaching, runoff or erosion. Due to the huge population and demand for food, intensive agriculture and incorporation of huge amount of chemicals are common in Asian countries. According to FAO's prediction, 60% of the world population will increase in Asia (FAO 2014). Therefore, in Asia easy availability of food for this exponentially growing population is a major concern for policymakers and scientists. High yield and vegetative growth of crops obviously depend on nitrogen application and the demand of the particular crop for nitrogen, whereas losses deteriorate the environmental quality and human health (Vitousek et al. 2009). Level of economic development also affects the balance of nutrients that differs among different Asian countries (Vitousek et al. 2009). Six different countries were examined in a study starting from developing (China and India), developed (Japan and South Korea) to least developed countries (Laos and North Korea). Highest amount of nitrogen input was observed in China, i.e. 505 kg N ha^{-1} of cultivated land. In least developed countries, previously manure was taken as the nutrient source that is precious for crop growth. The story for China was same before the artificial fertilizer was subsidized. But, after the fertilizers were subsidized from 1980 onwards, the rate of fertilizer application in China even exceeded that of the USA and EU (Ju et al. 2009; Vitousek et al. 2009). In 2005, lack of regulation on discharge of manure has led to half of manures being dumped into water bodies in untreated condition in China (Ma et al. 2010). The N that is applied and the output varied differently for different crops. The highest input of nitrogen and the accumulation in produced cash crops were reported in China (Yan et al. 2013a, b). As the production of cash crop and livestock is expected to rise in Asia in near future (FAO 2014), it is the need of the hour to develop sustainable strategies to improve the nitrogen input and output.

More than 100% nitrogen use efficiency was observed in countries like Laos, Nepal and Myanmar as they generally recycle inputs like manure and crop straw. The N surplus in the countries showed a reverse trend from high N depleted countries like Nepal and Laos to the high N surplus countries such as the United Arab Emirates and China. In high N depleted or surplus countries, no cropping systems were found sustainable. On the other hand, higher nitrogen use efficiency and lower N losses were recorded in least developed countries but the increasing N losses will severely hamper the food production. In countries with surplus nitrogen, the continuous N accumulation causes high N losses and related environmental problems (Guo et al. 2010; Liu et al. 2013).

35.5 Case Studies in India

35.5.1 Degraded and Wastelands of India

20 Agro-Ecological Regions (AERs) have been identified and those are further subdivided into 60 Agro-Ecological Sub-Regions. Inceptisols stand the dominant soils covering 39.75% of the total area, which is followed by Entisols (28.08%), Alfisols (13.55%), Vertisols (8.52%), Aridisols (4.28%), Ultisols (2.51%), Mollisols (0.4%) and others (2.92%) (Bhattacharyya et al. 2013).

The total area that is exposed to soil degradation in India is 45.9% as reported by Velayutham and Bhattacharya (2000). Out of this area, 37.0% is affected by water erosion, 4% by wind erosion, 2.2% by salinization, 1.1% by loss of nutrients and 1.6% by waterlogging. Based on the database by different organizations compiled by the National Academy of Agricultural Sciences (NAAS) it was observed that the most common mode of soil erosion was by water affecting 82.57% of the total area, which was followed by 12.40% of wind erosion, 17.94% of acidic soil, 6.74% of salt-affected soil and 0.88% of waterlogged soil and 0.19% of mining, industrial waste which is depicted clearly in Table 35.1 (degraded and wastelands of India).

35.5.2 Environmental Impacts of Tannery Industries in India

Wastes from tanning industries contaminate the surface water bodies with effluents constituting high oxygen demand and other toxic chemicals causing discolouration

Table 35.1 Degraded and wastelands of India (Source: ICAR and NAAS 2010)

Degradation type	Arable land (million ha)	Open forest (<40% canopy) (million ha)	Data source
Erosion			
Water erosion (>10 tonnes ha^{-1} $year^{-1}$)	73.27	9.30	Soil loss map of India–CSWCR&TI
Wind erosion (Aeolian)	12.40	–	Wind Erosion map of India–CAZRI
Sub-total	85.67	9.30	
Chemical degradation			
Exclusively salt-affected soils	5.44	–	Salt-affected soils, map of India, CSSRI, NBSS&LUP, NRSA and others
Salt-affected and water eroded soils	1.20	0.10	–
Exclusively acidic soils (pH <5.5)	5.09	–	Acid soil map of India, NBSS&LUP acidic (pH <5.5) and water
Acidic soils (pH <5.5)and eroded soils	5.72	7.13	–
Sub-total	17.45	7.23	
Physical degradation			
Mining and industrial waste	0.19	–	Wasteland map of India–NRSA
Waterlogging (permanent surface inundation)	0.88	–	–
Sub-total	1.07	–	–
Total	104.19	16.53	–
Grand total (arable land and open forest)	120.72	–	–

of colour (Song et al. 2000). Tannery waste comprised of both organic (chlorinated phenols) and inorganic (chromium) pollutants (Mwinyihija et al. 2006). Other pollutants that are of concern include azo dyes, cadmium compounds, cobalt, copper, antimony, barium, lead, selenium, mercury, zinc, arsenic, polychlorinated biphenyls (PCB), nickel, formaldehyde resins and pesticides residues. When these particular pollutants are released into the environment, they cause antagonistic effects on air, water and soil quality. A WHO report suggested that more than 8000 workers in the tanneries of Hazaribagh, India had to fall prey to various dermatological and gastrointestinal disorders, which may limit their lifespan by about 50 years (Maurice 2001). Chromium exposure has also led to respiratory diseases and a significantly higher morbidity among workers of tannery industry (Rastogi et al. 2008).

35.6 Climate Change: An Impact of Human Disturbance

According to the Inter-governmental Panel on Climate Change (IPCC), climate change is defined as change in climatic conditions over time, due to human activities or natural variability. The given definition differs from that of the Framework Convention on Climate Change (FCCC), which defines the change in climate is directly or indirectly attributable to the human activities, which alters the global atmospheric composition, and is applicable to the natural climatic variability. According to IPCC data for last 2000 years, the atmospheric concentrations of CO_2, CH_4 and N_2O and other relevant long-lived greenhouse gases have increased substantially since 1750. The rate of increase had been dramatic, for instance, CO_2, never increased for more than 30 ppm during previous 1000-year period but has risen by 30 ppm in the past two decades. In accordance to this record, during the period of 1995–2005, i.e. during last ten years, the average growth rate of annual carbon dioxide concentration was 1.9 ppm. In a large view, the increase in greenhouse gas concentrations and the change in alarming rate are mostly attributable to human activities since Industrial Revolution (1800). The increase in current atmospheric levels of greenhouse gases are results of the competition between sources (the emission of gases due to natural processes and human activities) and sinks (the removal from atmosphere by conversion to different chemical compounds, like, carbon dioxide is removed by photosynthesis and conversion to carbonates). The following Figs. 35.5, 35.6, and 35.7 depict the brief summaries of the important greenhouse gases, their sources like the human contribution and the natural sources and the sinks.

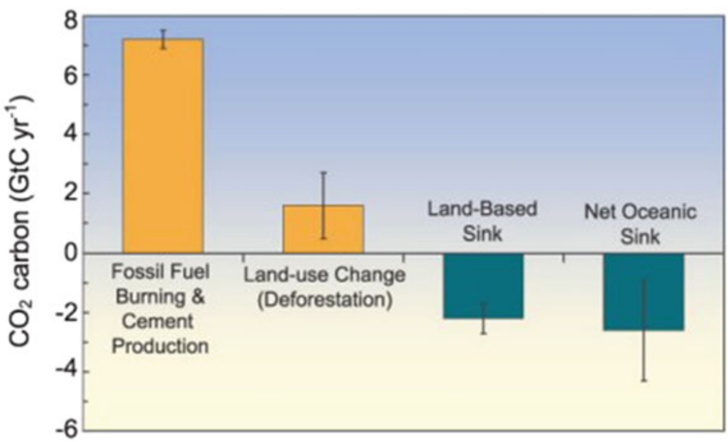

Fig. 35.5 The sources and the sink for carbon dioxide (IPCC 2007)

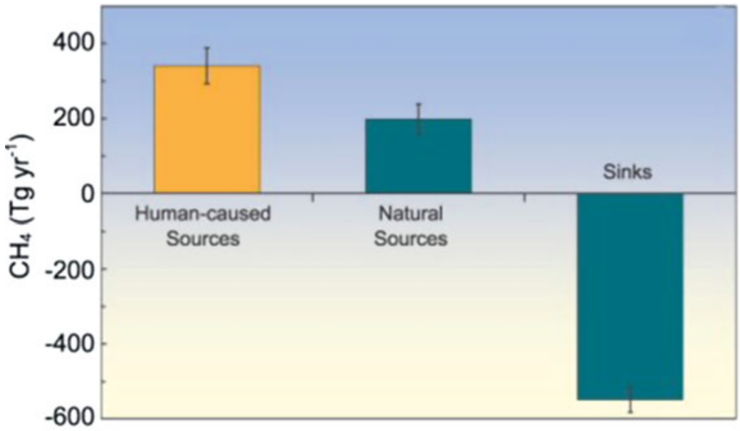

Fig. 35.6 The sources and the sink for methane (IPCC 2007)

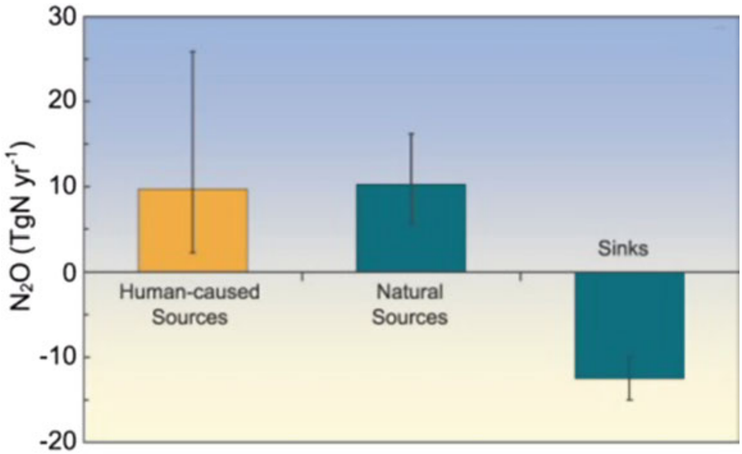

Fig. 35.7 The sources and the sink for nitrous oxide (IPCC 2007)

35.6.1 General Causes of Climate Change

The energy balance between the climate and the land surface is generally changed due to the greenhouse gases and the aerosols present in atmosphere and the solar radiation. The changes are generally expressed in the terms of radiative force, which is a measure of an influencing factor that alters the balance of incoming and outgoing energy in the earth-atmosphere system. It can also be considered as the index of the importance of the factor as a potential climate change mechanism and is used to compare the range of human or natural factors that drive the warming or cooling effect on the global climate (IPCC 2007). IPCC also stated 'Taken as a whole, the range of published evidence indicates that the net damage costs of climate change are likely to be significant and to increase over time'.

The causes of climate change are either man-made or natural.

Natural Drivers Earth's climate is always changing due to dynamic processes undergoing in nature. Scientists studying on climate change all over the world are acquiring information from tree rings, pollen samples, ice cores and sea sediments. Prominent natural factors responsible for climate change are continental drift, volcanoes, ocean currents, the earth's tilt, comets and meteorites (Karmakar et al. 2015).

Man-Made Causes Rapid industrialization and urbanization have led to increasing emission of greenhouse gases. This is eventually trapping the heat over the earth surface, which is a primary reason for the rise in temperature of the earth. Human activities have certainly increased the emission of carbon dioxide to such an extent that even the forest cover, ocean and the soil taken together are not able to absorb it at that faster rate from the atmosphere.

Miscellaneous Activities It has been proved that local land use pattern affects the local climatic conditions (multinational) (Allan et al. 1995; Claussen et al. 2001), as well as somewhere far off that place. For instance, forest fires, deforestation, mining and related activities can affect the local climate as well as aggravate the rise in temperate of the atmosphere as a whole due to increase in release of greenhouse gases.

35.6.2 Greenhouse Gases: Major Cause for Global Warming

The cover of atmospheric gases over the Earth's surface makes it suitable for the existence of life as it mainly regulates the temperature. Without the presence of these atmospheric gases there would have been extremes of temperature. As the short wavelength of light enters the earth surface, long wavelength is reflected back which is trapped by the greenhouse gases, giving the earth an average temperature of 15 °C. In absence of the earth's atmospheric cover, the temperature would have been −18 °C (Rakshit et al. 2009). Therefore, the blanket of gases acts like a greenhouse increasing the temperature on earth and making it habitable. This phenomenon is known as 'Greenhouse Effect'. As discussed earlier, the various greenhouse gases like carbon dioxide, nitrous oxides and sulphur oxides along with water vapour and mainly chloro-fluoro carbons (CFCs) released from various sources are increasing rapidly day by day. This results in trapping of more solar radiation with subsequent increase in temperature leading to far reaching effect on various ecosystems. However, it was estimated that the global mean surface temperature increased by 0.5 °C due to emissions and this concentration may raise the temperature of earth surface by 1.5 °C over the next 40 years (Mitchell 1989).

89% of the total area is accounted for rice cultivation in Asia (Yan et al. 2003). Apart from feeding a majority of the population, rice is the prime source of greenhouse gases like methane and nitrous oxide. Both the gases have a considerable capacity of absorbing infrared radiation in comparison with carbon dioxide on a mass basis, i.e. 25 times for CH_4 and 298 times for N_2O. Undergoing the tier 1 method that was described in 2006 by IPCC for National Greenhouse Gas Inventories (IPCC 2006), Yan and colleagues estimated the global CH_4 emission for 2000 was 25.6 Tg CH_4 year^{-1}, with a 95% uncertainty range of 14.8 to 41.7 Tg CH_4 year^{-1}, lower than the previous estimates (Yan et al. 2009). Three main processes mainly regulate the emission of methane from rice fields—production, oxidation and transport. These factors generally influence other factors like organic amendment and water content in soil during rice growing season and status of water in pre-season. Therefore, regulations of these factors are very important and techniques may include off-season straw incorporation and mid-season drainage (Yan et al. 2009). Most of the nitrous oxide emissions happen after mid-season drainage and nitrogen fertilizer additions (Yan et al. 2000). Average 0.3% fertilizer induced N_2O emission occurs from rice fields that fluctuates depending on fertilizer additions (Yan et al. 2000). Figure 35.8 represents the estimated CH_4 emission from paddy in Asia, and Fig. 35.9 depicts the Asia-Pacific emissions from different sectors and the highest percentage is emitted by industries followed by energy, agriculture and waste.

35.6.3 Direct and Indirect Effect of Climate Change

35.6.3.1 Direct Impact on Soil Functions

According to some soil climate models, the organic matter turnover increases with the increasing temperature, precipitation and evaporation. Therefore, any rise in temperature fastens the rate of reactions in soil, increasing the rate of release of CO_2, both in mineral and organic soils. All the soil functions are interrelated and a slight change in one or two can trigger series of changes in the others. Release of CO_2 from the soil due to increasing rate of soil reactions can cause impact on other physical properties like structure, stability, water holding capacity, nutrient availability, leading to soil degradation and erosion. Aberrant rainfall patterns can either result in submergence, formation of peat and release of methane in the atmosphere for higher precipitation or loss of CO_2 and less nutrient availability due to less precipitation. The effects of the variation in rainfall pattern can directly be associated with the soil invertebrates and their life cycles, which is collectively associated with change in foraging and reproducing pattern of various organisms in the food chain (Sangle et al. 2015). Fate of pesticides and other agricultural chemicals are also dependent on the complex interactions between the environment, the nature of vegetation and the microbial interaction within the soil. Their persistence in the soil system largely depends on the moisture available; therefore, precipitation plays an important role for determining that.

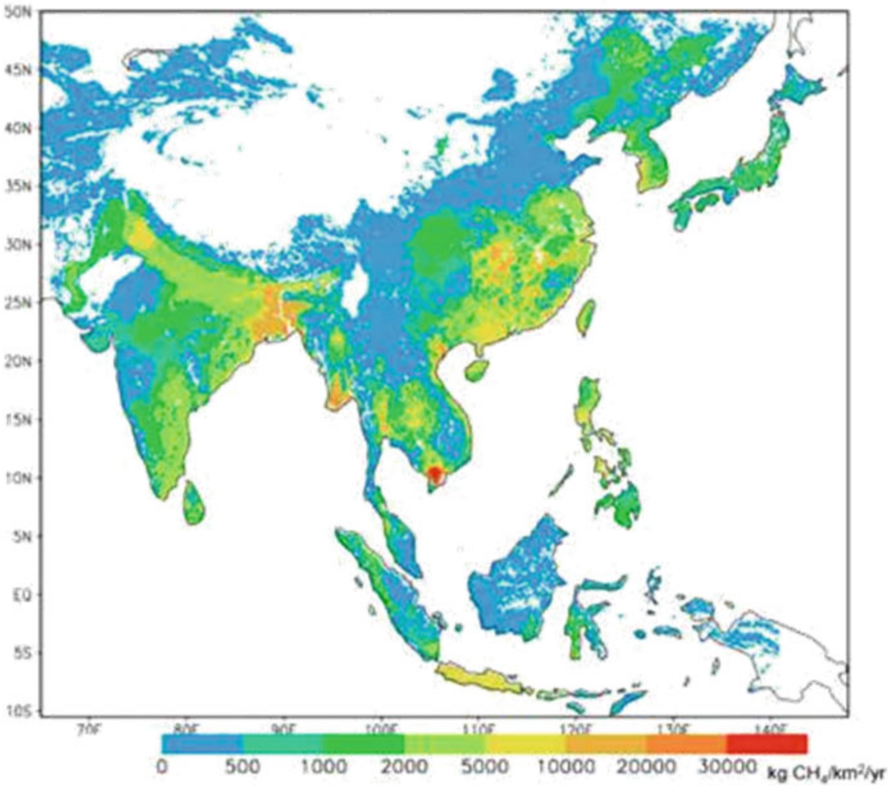

Fig. 35.8 Estimated CH_4 emission from paddy in Asia (Source: Yan et al. 2009)

35.6.3.2 Indirect Impact on Soil Functions

For the plant species having C3 photosynthetic pathway, the effect of climate change can result in increase in yield (winter wheat, sunflower), as they receive most congenial factors like, more CO_2, radiation and longer growing seasons (Pathak et al. 2012; Mihra and Rakshit 2008). However, reverse phenomenon happens for plants with C4 pathway (Allen Jr. et al. 1996). For most of the C3 plants, the elevated CO_2 levels and the availability of light lead to growth of more structural components. More photo-assimilates are transferred to the vegetative structures in order to support the light-harvesting apparatus, i.e. leaves (Allen Jr. et al. 1996). Therefore, we can expect increase in yield of the crops like sunflower, whereas yield of C4 crops as well as horticultural crops can have drastic fall in their harvest index.

Thus when productivity of the crop increases, the leaf litter fall will certainly increase the soil organic matter (DEFRA,2005) which may have the following significance:

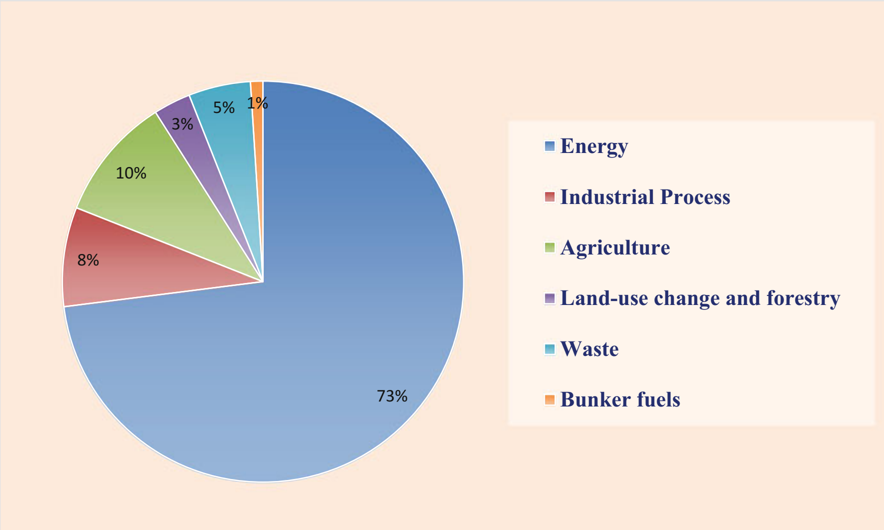

Fig. 35.9 Asia-Pacific emissions by sector, including land use change and forestry, 2014 (percentage) (Source: Based on data from World Resources Institute, CAIT Climate Data Explorer. Available at http://cait.wri.org)

- How precipitation and temperature control the level of C above and below-ground carbon and the decomposition and turnover of Soil Organic Matter.
- The harvest index of different crops in changing climatic patterns.

Table 35.2 depicts the time scale for changes in soils with change in climate (DEFRA 2005). It is quite clear from the table that in a short span of time due to the effect of the changing climate properties like temperature, porosity, water holding capacity varies and the last to undergo change is texture.

35.7 Vulnerability of Asian Countries to Climate Change

More extremes of temperature were recorded in continental interiors of Asia, and from 1979 onwards, it was more prominent over China in winter, and northern and eastern Asia in spring and autumn (Hijioka et al. 2014). Precipitation increased significantly in northern and central Asia but declined in parts of southern Asia from 1900 to 2005 Asia. Scarcity of water resource and rapid melting of glaciers may stand as an outcome for future climate change (Hijioka et al. 2014). Climate change may enhance the risk of extinction for a number of plant and animal species and subsequent habitat fragmentation may occur. The pressure on natural resources may increase many folds due to exponentially growing urbanization, industrialization and economic development. People dwelling along the coasts of South and Southeast Asia will be at risk from flooding which in long run may impact the food production

Table 35.2 Time scale for changes in soils with change in climate (DEFRA 2005)

Time scale	Soil parameter	Properties
$<10^{-1}$ year	Temperature, moisture content, bulk density, total porosity, infiltration rate, permeability, composition of soil air and nitrate content	Compaction and drainage
10^{-1}–10^{0} year	Total water capacity, field capacity, hydraulic conductivity, pH, nutrient status and composition of soil solution	Microbiota
10^{0}–10^{1} year	Wilting percentage, soil acidity, cation capacity exchange and exchangeable cations	Type of soil structure, annual roots biota, meso-fauna, litter, gleyic, properties and slickensides
10^{1}–10^{2} year	Specific surface, clay mineral association and organic matter content	Soil biota, salic, calcareous, sodic and vertic properties
10^{2}–10^{3} year	Primary mineral composition and chemical composition of mineral part	Tree roots and colour (yellowish/reddish), iron concretions, soil depth, cracking, soft powdered lime and indurated sub-soil
$>10^{3}$ year	Texture, particle-size distribution and particle density	Parent material, depth and abrupt textural change

in different regions (Hijioka et al. 2014). Mainly the coastal and riverine areas are at a very high risk because of rapid developmental processes. Second confidence is imposed on the fact that decreasing precipitation, increasing population and expanding water withdrawal have exacerbated the water scarcity in northern China (Xu et al. 2010). Degradation of water quality was also observed in some regions of Asia (Delpla et al. 2009; Park et al. 2010), which was highly influenced by human activities (Winkel et al. 2011). Melting of glaciers has shown a heterogeneous pattern in Asia (Gessner et al. 2013). Changes observed in the Kamchatka glaciers were caused by both warming and volcanic activity, with the area of some other glaciers decreasing (Anisimov 2009).

Maximum amount of biological changes were observed in the north high altitudes, and a few in tropical lowlands, which was mainly linked to the climate change. The inland water systems are also tangled in the impacts originated from climatic variability (Vörösmarty et al. 2010). The Aral Sea is shrinking over the last 50 years which is a consequence of extracting water injudiciously from rivers and is further accelerated by increasing temperature and decreasing precipitation (Lioubimtseva and Henebry,2009; Kostianoy and Kosarev 2010). The steppe region of northern Kazakhstan demonstrated an overall browning (decreasing Normalized Difference Vegetation Index) in the year 1982–2008, which can be linked to declining precipitation (de Jong et al. 2012). Normalized Difference Vegetation Index (NDVI) is quite sensitive to precipitation in Central Asia (Gessner et al. 2013), the pattern was heterogeneous for 1982–2009, with an initial greening (Mohammat et al. 2013). For temperate East Asia, tree-ring data for 800–1989 shows that recent summer temperatures have past those during similar length warm periods, but the difference was not statistically significant (Cook et al.

2012). Large changes are expected to occur in North Asia in terms of potential natural ecosystems due to rising temperatures (Pearson et al. 2013). In China's most productive wheat growing region, Huang-Hai Plain a modelling approach indicated an increase in average yield by 0.2 Mg ha^{-1} in 2015–2045 and by 0.8 Mg ha^{-1} in 2070–2099, which can be attributed to higher night temperature and precipitation, using HadCM3 model (Thomson et al. 2006). According to a probabilistic projection maize yield will change by −9.7 to −9.1%, −19.0 to −15.7%, and − 25.5 to −24.7%, during 2020s, 2050s, and 2080s as compared to −15.7%, and − 25.5 to −24.7%, during 2020s, 2050s, and 2080s of 1961–1990 yields (Tao et al. 2009a, b). On the other hand extremes of temperature probably could have negative effects on yield of rice (Mohammed and Tarpley 2009; Tian et al. 2012). Central Asia is expected to turn even more arid especially in the western parts of Turkmenistan, Uzbekistan and Kazakhstan (Lioubimtseva and Henebry 2009). Where some parts may benefit from the increasing temperature, especially in terms of yield, others are going to face serious threats, particularly in western Turkmenistan and Uzbekistan, the cotton production can get largely hampered due to increasing demand for irrigation water. Indo-Gangetic Plains in India are also under risk of significant decline of wheat yields (Ortiz et al. 2008). The deltaic rice production is threatened enough due to sea level rise, like in Bangladesh and the Mekong River Delta (Wassmann et al. 2009b). 7% of Vietnam's agriculture land may face submergence due to 1 metre sea level rise (Dasgupta et al. 2009). Intrusion of saltwater due to sea level rise may also decrease rice yield in Myanmar (Wassmann et al. 2009b).

35.8 Food Security of Asian Countries

According to a report by Food and Agricultural Organization (FAO 2018), for monitoring the progress in the second sustainable Development Goal by G20, in which countries are called to 'end hunger, achieve food security and improved nutrition and promote sustainable agriculture' by 2030, the estimates were quite concerning. They confirmed the immediate need for the international community to come forward and lend hands in promotion of different policies regarding actions towards a sustainable development. It appeared quite challenging task to eliminate hunger and malnutrition by 2030 and it needs untiring efforts by the international levels regarding policy making and implementation.

With the increase of income in the low and middle-income countries, a shift may occur from diet based on cereals to consumption of more of meat, fruits and vegetable, which will increase the load on the natural resources (FAO 2018). It is estimated that per capita calorie availability will increase significantly in developing countries. The consumption of certain levels of vegetable oils and sugar will still be a factor that will add on to the problem of malnutrition continuing the food insecurity and making it a global concern.

The staple food of Asia is Rice and 90% or more of it is produced in Asia. A study mainly concerning the rice growing areas of Asia revealed that rice yield would reduce over a huge portion of the continent (Masutomi et al. 2009) with the most vulnerable regions being western Japan, eastern China, the southern part of the Indochina peninsula and the northern part of South Asia. 'Food production shortfall' in Russia may be an event which can be co-related with climate change implying climate related annual potential of most important crops in an administrative region in a specific year average below 50% of the climate normal (1961–1990) (Alcamo et al. 2007). The main reason behind the shortfalls is drought. The extremes of climate in various part of the continent may pose a great risk towards its food security due to subsequent changes in soil and vegetation.

In contradiction to the above situation, climate change may have some beneficial effects on wheat in Pakistan. The warmer temperatures support growth of at least two crops, maize and wheat in a year on the mountain areas (Hussain and Mudasser 2007). In the northern mountains of Pakistan wheat yield increased by 50% as determined under SRES A2 and by 40% under the B2 scenario, but in sub-mountainous, semiarid, and arid areas, it may decrease by the 2080s (Iqbal et al. 2009). It is therefore obvious that food production and food security are mostly vulnerable to the increasing air temperature (Wassmann et al. 2009a, b). Therefore, the notion developed is that rising temperature on the one hand is responsible for declining yield of rice. On the other hand, it may prove beneficial for food production (Lioubimtseva and Henebry 2009).

So, in some areas temperature changes have proved to be a constraint in food production challenging the food security of the region. Therefore, it is mandatory to undergo crop-specific and country specific adaptation measures.

35.9 Adaptation Strategies for Soil Conservation

Soil stands as the important natural resource in relation to food security and livelihood generation. Therefore, maintaining the soil quality should be treated as a priority for obtaining a steady productivity. From the earlier segments of this chapter it is clear that already human intervention is causing a great stress on our natural resources including soil. The problem is further aggravated by the climate change as an indirect effect of development. Many indigenous and local management strategies were undertaken by farmers in Southeast Asia to mitigate the adverse effect of climate change in Asia (Peras et al. 2008; Lasco et al. 2010). Crop breeding serves as a promising option in Asia. In the North China Plain there are varieties that can withstand high temperatures and using those varieties in 2050 maize yield could possibly increase by 1.0 to 6.0%, 9.9 to 15.2%, and 4.1 to 5.6% if some strategies like early planting, fixing variety are adapted, respectively (Tao and Zhang 2010). Therefore, apart from efficient policy making and implementing, different soil and crop management strategies are also important at farmer's level, to fulfil the purpose.

Adaptation measures include:

- Appropriate decision making regarding cultivation practices like time of planting, number of tillage, number of irrigation, variety selected.

- Undergoing soil moisture conservation practices like mulching, irrigation scheduling can protect the soil from water erosion.
- Judicious use of chemical fertilizers and pesticides along with timely application. A number of herbicides and fungicides are reported to kill the soil beneficial microbes (Ingham 2003).
- Addition of organic manures, straws and residues to increase the carbon sequestration. Research has shown that organic matter application adds tonnes of bioavailable carbon which is beneficial to the plants as well as soil microbes and assists in the process of topsoil formation. Humus and glomalin that are stable forms of carbon are processed by microorganisms that are essential for soil health (Ingham 2003).
- Rotation of crops must be practiced and surface soil should remain covered to avoid erosion and to hold the soil particles in place.
- Conservation of wetlands and coastal habitats because they are most vulnerable to land use and climatic changes.
- Reduction in application of nitrogenous fertilizers as in excess they undergo denitrification losses causing nitrous oxide pollution or leaches to pollute the groundwater.

35.10 Conclusion

The whole chapter focussed on the impact of human intervention on soil properties in the light of food security and sustainability. Therefore, to meet the nutritional requirements of a vast country like Asia, the emphasis must be given on the utilization of the natural resources in a sustainable manner. Soil being a significant resource and a part of our growth and development should be managed in a strategic planning. Without healthy soil, there is no possibility of optimum productivity. As intense human disturbances in the form of multiple sectors are intensively drawing out requirements from the natural resources, the sensitive resources are exposed to various pollutants that are gradually destroying them. This has led to a numerous change in the type of vegetation and habitants. Therefore, to cope up with the existing alarming situation, initiative should be taken at international policy maker side as well as awareness should be spread among the population regarding the tentative outcome of the injudicious utilization.

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Part IV

Case Studies on Various Status and Practices of Soil Management: Indian Story

36 Natural Resource Management and Conservation for Smallholder Farming in India: Strategies and Challenges

Dibyendu Mukhopadhyay and Princy Thakur

Abstract

There are limitations on the horizontal expansion of the land and one can foresee only the remote chances of bringing more areas under the plough, particularly in some pockets of Asia and Europe. We need to explore on the available resources of land and water for agriculture in a judicious way so as to bring more barren area under the cultivable lands. It has been observed that due to the unscrupulous distribution of the non-farm uses and growing rate of concern of soil and water quality, our standing forests are decreasing and groundwater reserve is also depleting. There is an alarming situation of productive areas under the threat of floods and droughts. Besides, there is an increasing demand of good quality water for irrigation and drinking purpose which is now become difficult to achieve due to the contamination caused by industrial effluents and domestic sewage. A constant challenge is there to evolve sustainable and equitable management of existing water resources. It requires to have stabilized water management strategies on scientific data on quantity and quality of water, demand for water and economically viable technology adopted for judicious use of water to the stakeholders. There should be avoidance of piece-meal approaches to solve sectoral problems. The need-based interest of the stakeholders is to be prioritized to ensure equitable allocation and improving water-use efficiency in agriculture. However, the close proximity of land and water in mobilizing available nutrients to the crops needs to be addressed. The same piece of land may act both as a source and sink for the pollutant elements leading to the groundwater pollution.

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Keywords

Groundwater · Nutrients · Sustainable · Toxicants · Use efficiency of water · Land use

36.1 Introduction

Among the most important natural resources, good soil and water are the matter of concern to retain sustainable production processes in agriculture. For this reason, the cropping intensity needs to be increased by converting more of the degraded land into cultivable one. There is a need to develop the global monitoring information system on soil and water to provide the information needed for soil-water management and to monitor progress against targets. This will provide a wide spectrum of information from the local level and up to the National and Global levels (e.g., monitoring data, public documents, comprehensive national plans, available and appropriate technologies). The comprehensive and forward-looking information and the gradual development of the capacity to streamlining the information into the decision making process are a mean to allow people and institutions to access new insights and innovations.

It has been reported that (FAO and WWC 2015) with appropriate investment and policy interventions, food production will be sufficient to support a global population in 2050 although food and nutritional insecurity will sustain in many regions. Countries in water scarce regions will increasingly need to devise food security strategies that explicitly consider structural food supply deficit and trade arrangements that will provide protection from food price fluctuation. Higher pressures on water for food production may be expected because large segments of the populations in the emerging countries will tend to raise their standards of living by changing the habit of growth.

The problem on water scarcity may affect about two-thirds of the world's population within decades. The problems may be reduced by increasing surface and groundwater storage and allocation through the creation of new infrastructure, desalination of saltwater or brackish water, reuse of wastewater or recharging aquifers. By stemming the losses in transport and distribution systems, implementing adequate tariff systems, changing water use technologies and increasing the efficiency of water use in domestic, industrial and irrigation systems may increase overall water productivity of a region. Improving the governance policies and procedures in time the Nation can keep pace with the demand for water globally (International Food Policy Research Institute (IFPRI) 2012) as because providing healthy and meaningful livelihoods for all should be the challenge in this century.

It has been observed that the average annual rainfall is nearing 2500–3000 mm in the north eastern part of India and much of the water is lost along with the surface soil due to the want of sufficient water harvesting or water-storing structures and similarly for soil conservation measures. It is only the stabilized water and soil management strategies with viable technology to solve the problems which have a direct bearing to reduce the load of heavy metals (arsenic, fluoride, cadmium, lead, etc.) in the food chain. Care should be taken on need-based interest of the stakeholders to ensure equitable allocation of natural resources (as admissible) in agriculture. However, a detailed survey on land use and land cover is required for understanding the soil-site suitability for crops in a particular region. This will also help planning nutrient budget for crops in a sequence and thus directing efficient fertilizer management planning to avoid nutrient toxicity to the crops. In India, 80% domestic water is supplied from groundwater and more than 20 million tube wells collectively account for 50% of irrigated water and 15% of India's food are produced from groundwater (World bank group). Hence, the judicious utilization of groundwater for irrigation is required to save the nation and the ecology as well.

36.2 Soil Management

Soil management is the operational arrangement to safeguard the fertility status of soil through soil conservation, soil amendment and thus maintaining soil health and resilience. Efficient soil management is required to achieve success in site-specific nutrient management according to soil conditions and needs. This in turn improves sustainability and lowers down the production costs in field. The conservation and minimum tillage (the practice of leaving residues on the soil surface) can reduce the soil disturbance. The physico-chemical parameters of soils are important to seed and fertilizer placement which may contribute to increase yields at reduced unit costs. The comprehensive strategies (Fig. 36.1) of soil management will lead to enhance and restore the fertility status of soil and thus focusing more on the resource conservation in agricultural production.

The judicious application of chemicals in proper proportions is of environmental and economic concern to farmers. Using a GPS (Global Positioning System) along with a digital map or application map, a farmer is able to apply inputs in the field based on the available soil characteristics in each area of field.

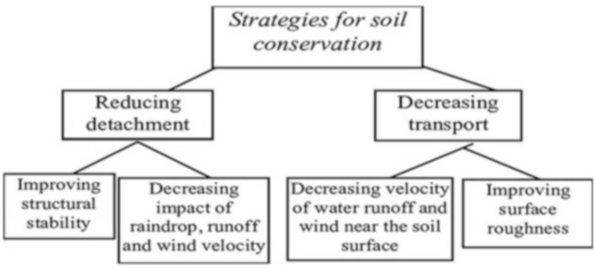

Fig. 36.1 Soil management strategies for soil conservation (Lal 2001)

36.2.1 Factors Affecting the Soil Management

36.2.1.1 Cultural Practices

Indigenous methods of practices can reduce much of the soil erosion and improve the fertility status of soil. In the mountainous regions, the fields are drought and weeds are removed with indigenous tools. However, the fertility status of soil in the lower field may be improved when nutrient-rich soils are added from the bunds of upper field to the lower field. The broadened plough by attaching flat wooden pieces to both sides of the iron blade can stabilize the loose sandy strata in one ploughing action, which suits the small terraces in the upper valleys.

36.2.1.2 Sheet Erosion

This type of erosion which are common in forestland could account for the loss of billions of tonnes of soil every year. The particles are knocked loose and then carried away by the runoff due to rain drops. The sheet erosion results into rill and gullies. Surface covered with grasses, shrubs, etc. and rotational grazing during certain periods of times are allowed. The hedges can slow the runoff, weaken the erosive power of water and cause it to deposit its load of soil behind the hedge rows. As a result, the runoff losses are controlled. Besides, the erosive capacity of stream flow is also reduced by spurs of loose boulders at the bottom of the hills.

36.2.1.3 Rainfed Farming Systems

The rainfed farming system is in vogue in the hilly regions having limited irrigation facilities except in the valley. Hence, low water requiring crops are grown here and mixed cropping system is introduced. Growing of close-growing crop can reduce the sheet erosion and provide protection to the soil.

36.2.1.4 Cultivation in Slope

The terraces are constructed across the slope, i.e., along the contour line and the size of the terrace is decided by prevailing degree of slope. The roots of grasses help in binding and keeping the boulders intact at a place. The roots of grasses help in drainage of excess water. With the traditional knowledge, farmers are keeping the risers toward inner slopes. The bunding and terracing are continuing from centuries and terraces are still intact. The bunds are again used for growing palatable grasses which are used as fodder for livestock and trees are meant for fuel, fodder and fibre. Besides, it requires to take appropriate measure for the productive thin surface layer of soil against wind erosion which become less eroded when the soil is moisten or frozen. Cultivation at the levelled or flat land also checks soil erosion. Terracing in sloppy land not only helps conserving soil erosion but also proper use of irrigation water can reduce the surface runoff. In some cases, loose boulders spurs are also used to check soil, the cutting effect of stream flow in a productive soil.

36.2.1.5 Bearing Capacity of Soil

A soil is considered to be compacted when the total porosity (in particular, the air-filled porosity) is so low to restrict aeration, as well as when the soil is so tight and its pores so small, so as to impede root penetration, infiltration and drainage. The surface crust may form overexposed soils under the beating and dispersing action of raindrops, followed by drying and hardening of that surface layer. Indurated layers, called hardpans, can be of variable texture and in extreme cases, may exhibit rocklike properties. Such indurated layers, called fragipans, may become almost totally impenetrable to roots, water and air.

Sometimes, a claypan is developed which is relatively impermeable to water and air. In humid climates, such layers may remain perpetually wet and give rise to perched water tables above them, thus inducing anaerobic conditions within the root zone. Besides, the most common cause of soil compaction in modern agriculture is the use of heavy machinery, including tractors and other vehicles, as well as soil-engaging implements and by tillage tools operating beneath the surface. Prevention of soil compaction is the avoidance of all but truly essential pressure-inducing operations. This calls for minimizing tillage and choosing the efficient implements for timely application in the cultivable land.

36.2.1.6 Management of Soil Structure

Good soil management is associated with maintaining or improving the soil's physical condition (i.e., soil structure, aeration, water intake and retention) and its chemical conditions as well (pH, concentration of nutrients, toxic factors, etc.). Maintaining the surface-protecting residues (stubble) of previous crops and to plant a new row-crop by opening narrow slits in the soil with minimal disturbance of the inter-row strips, known as "no-till" or "minimum tillage" farming may be introduced.

36.2.1.7 Fertility Management of Soil

A sustained level of soil management is required for building up of soil fertility for the profitable use of agricultural lands. The chemical fertilizers add up concentrated supplies of readily available plant nutrients to the soil while the beneficial effect of organic manures predominantly lies in furnishing humus forming material to bring about improvement in the soil structure, water holding capacity, microbial population and its activity, base exchange capacity and resistance to soil erosion. The organic matter addition can restore nutrient stock in soil which was removed by the crops during cultivation.

Management by Crop Residue

The stumps are pulled out by hand along with the complete root system. Soil is softened by a light irrigation a day before. Wheat is often pulled out while standing, but kneeling or squatting is practiced for barley. Harvest of crops just above the surface soil could provide minimum disturbance to the soil and thus avoid loosening of soil. The roots are made to stay in soil for humus production. Very little plant material (stem and roots) is allowed to be left in the soil as a protective measure against the soil-borne diseases. Due to the retention of roots in soil, humus availability is increased which improves the soil structure, porosity and water holding capacity of the soil.

Addition of Organic Materials

The bulk of organic manures derived from plant and animal resource are the manures that supply the plant nutrients, e.g., farm yard manure, rural and town compost, night soil, green manure, etc. and the concentrated organic manures, e.g., oil cakes, goat manure, sheep and poultry manure, blood and meat-meals, etc. are used to increase the fertility status of the soil as well as aggregate stability of the soil. Periodical collection of the leaves and grasses which are used as bedding for the animals, got soaked with the excreta/urine of livestock are used as manure in the field. Sometimes, the night soil which contains the major plant nutrients like nitrogen, phosphorus and potassium is mixed with soil from cultivated field to improve the soil fertility. The practice of collecting soil from cultivated land and fields helps in easy ploughing during summer cropping also.

36.3 Challenges and Opportunity

Soil the most valuable natural resource on earth requires nurture and care from time to time to make it productive in a sustainable manner. The soil erosion and its control have become one of the important aspects to maintain the top soil (0–20 cm) fertile on which the plants anchor at its initial phases. The sheet erosion or rill and gully erosion are some of the negative forces affecting the stability of the soil. It requires to identify the major problems and the strategies to scale the nature of soil management by carefully examining the processes of water and wind erosion along with techniques for soil conservation and also to address the inter-related problems of desertification and salinization of arid soils. This will ensure finding the extent and severity of the problems and the relative importance of human and natural causes. The issue of the amelioration of arid soils is to be considered, including the feasibility of desert reclamation and soil desalinization where optimal use of soil requires careful consideration of soil water. The soil pollution and its control are other important challenges of today. The problems posed by nitrate, phosphate, pesticides, heavy metals and pathogenic microorganisms have become a major issue on soil management. The various natural and industrial causes of soil acidification and the effects of acidification on plant, animal and human health are other challenges. The benefits and problems of zero and conventional tillage practises to maintain good soil structure are an issue. The problems of soil compaction and the reclamation and restoration of quarries, landfill sites and mine-spoil are also to be addressed. The value of crop residues and implications of peat wastage are to be taken care off. Climatic change and its role are currently receiving intense attention and soils play an important role in it. Soils affect the global carbon dioxide, methane and nitrous oxide cycles and budgets and possibilities for managing soils to minimize emissions of these “greenhouse” gases are adhere into. Hence, it requires suitable techniques for soil reclamation, rehabilitation, restoration to have a close link-up between soils and environmental health and to create avenues for improved soil management strategies for favourable habitation.

36.4 Water Management

The planning, developing, distributing and optimum use of water resources are to be addressed under the aegis of water management programme. The storing of water during the lean period of time is required for the irrigation purpose. In the southern part of India, where, rainfall is scanty, the practice of trapping rainwater in large tanks and ponds for agricultural purposes is widely adopted. Although, in most of the cases, surface irrigation is applied based on the slope of the land, nature of the soil, type of the crop and availability of financial support. The existing resources are further declining due to heavy biotic pressure and lack of management of existing resources. The demand of water [Billion Cubic Meter (BCM)] by the year 2025 and by 2050 (Table 36.1) for the irrigation, domestic and industrial purpose clearly envisages the requirement to meet the subsistence of the animal kingdom which may perhaps exceeds all available sources of supply. Most of our Agricultural/ Horticultural activities are carried out in rainfed conditions and this requires proper management for the available water to be utilized during dry season.

36.4.1 Methods of Irrigation

There are different methods of irrigation systems. What we require is to minimize the conveyance loss of water during the irrigation by employing the suitable management options.

36.4.1.1 Indigenous Method

The indigenous practice of using pitcher water as a source of irrigation on new orchard plantation in sandy loam/loamy sand soils or in areas of scanty rainfall is prevalent in temperate region. The roots draw moisture/water from pitcher placed in soil reduces the mortality of plants. The pitcher once filled, supply sufficient moisture for at least 2 weeks and then again is refilled with water. The bamboo channels (open) are used for irrigating the fields by making small holes at the internodes of open bamboo channels from where water gets trickled down in the field. These channels are placed along the natural gradients although there is non-uniformity of head for water trickling in system. Besides, in the initial stage

Table 36.1 Projection of water demand (adopted from IWMI 2007)

Sector		2000		2025		2050
	Total	% from groundwater	Total	% from groundwater	Total	% from groundwater
	BCM	%	BCM	%	BCM	%
Irrigation	605	45	675	45	637	51
Domestic	34	50	66	45	101	50
Industrial	42	30	92	30	161	30
Total	680	44	833	43	900	47

of watering vegetables or low water requiring crops people used to bring water to their fields with the help of buckets or containers.

36.4.1.2 Water Harvesting

This is one of the important methods of collecting water from the available sources that can be used during the need. There are different methods of collection of water.

36.4.1.3 Water Collection in Ditches/Ponds

The spring water in small reservoirs at intervals on uplands and then drawing water from these ponds when required are maintained. Water from these ponds is used for irrigating crops and also for drinking purpose when in need.

36.4.1.4 Harvesting Precipitating Water

The humidity remains quite high in the atmosphere after the rain. When the temperature falls down at night, water molecules from vaporous gradually fall on soil surface and make the soil moist and wet. If the soil is clayey in nature, retention of water remains for a longer time and becomes a source of soil moisture. It is quite useful for land preparation in October-November and for the sowing of *Rabi* crops like wheat, pulses and barley.

36.4.1.5 Roof Water Harvesting

Roof water is collected in dugout structures. These structures are dug in hard rocks. The roof water along with the surface water is collected in dugout structures for further use.

36.4.1.6 Rainwater Harvesting

Relatively a sizable percentage of rainwater goes as runoff and stream flow. It carries fertile soil and plant nutrients causing the soil degraded and barren. The excess water is stored directly in the ponds, depression or stream flow or is diverted to safer points where it is stored so that the stored water in ponds, dugout structures and depressions is used for irrigation purposes during lean periods as a supplementary source. In some areas during summer, it is used as drinking water for humans, livestock and also used for other domestic purposes.

36.4.1.7 Drainage

It has been customary that during the preparation of a field, the slope is kept inside which is provided with a channel to take excess water from that field to a safer place, from where it is disposed to streams or nalas through grassed water ways, but, improper drainage may cause water stagnation over the soil surface in a clay-textured soil. The vegetables which are water sensitive in some areas are susceptible to water logging. Hence, there should be proper draining facilities in a cropped land area where there is excess water.

36.5 Challenges and Opportunity

The time has already come to think over the possible renewable measures to restore the groundwater recharge by increasing the water use efficiency (WUE). The overdrawn of groundwater aquifers during the dry season polluted most of our waterbodies including estuaries, coastal zones and even oceans and degrade ecosystems to satisfy our short-term economic goals. The challenges of the current decade in the lithosphere and hydrosphere are resource constraints, financial instability, religious conflict, inequalities within and between countries, environmental degradation where water has become a central issue applicable not only to the freshwater systems but also to the oceans. The interdependence between social or human ambitions on the one hand and availability and quality of our natural resources on the other is obvious to determine the kind of realistic development in the society. Hence, comprehensive research is needed for better understanding of the complex interactions to be developed over the coming decades in association with the social, political and environmental implications as the issues on water will become even more important in the lives and activities of people (Cosgrove and Rijesberman 2000; Grayman et al. 2012). Because of the percentage increase in water use on a global scale has exceeded twice that of population growth, larger parts in the world are being subject to water stress.

To meet the nutritional needs of the increasing population, the amount of water that is consumed in the production of different goods and in particular, energy and food are to be accounted for. Hence, a complete analysis is required based on the protocol provided by the Comprehensive Assessment of Water Management in Agriculture [International Water Management Institute (IWMI) 2007].

In developed country, one can assume water of an average value of 200 L per person per day and the value adopted internationally for basic human water needs is about 50 L per person per day (Gleick and Iwra 1996). Although there is reduction in water use in agriculture, power plants, municipalities areas substantial progress has been made but the current water use trends are not sustainable in the context of population growth and climate change (Donnelly and Cooley 2015). The energy and water nexus are expressed both by the effects of water use on energy consumption and by the effects of energy production on water consumption (Hoff 2011; World Economic Forum Water Initiative (WEFWI) 2011; UNWWAP 2014). In this regard, the planner will need information about how climate change will affect probability in order to carry out risk-cost analyses of alternative investments in infrastructure needed in the future (Intergovernmental Panel on Climate Change (IPCC) 2012, 2014). Due attention should be given for measuring adaptation at the regional, watershed and household levels, such as water storage structures, conjunctive use of groundwater and surface water, wastewater capture and reuse, agroforestry and research that can generate more resilient production systems for the stakeholders. It requires to identify current and future climate hazards to conduct risk assessment inventory of infrastructure and assets and also to develop initial adaptation strategies for a better linkage to capital and rehabilitation cycles. Periodical monitoring on the prepared plans will sustain the required measure on the issues. (Grayman et al.

2012). The existing knowledge, the technology and the economic resources to manage our water resources through scientific research and systematic study of the structure and behaviour of the physical and natural world will definitely provide us the basic needs and right directions for the existing economic systems and for the public at large. Opinion surveys indicate a widespread worry in countries, e.g., the member states of the Organization for Economic Co-operation and Development (Organisation for Economic Co-operation and Development (OECD) 2011), about climate change and its probable effects. Still to achieve a water secured planet, it will be essential to get "more crop per drop", and "more jobs per drop".

Considering the advancement of the technological interventions, computer-based optimization and simulation models may be incorporated with interactive graphics, designs and policies that maximize the desired impacts and minimize the undesired ones (Grayman et al. 2012) will make us clear the basic and urgent need of the situation.

36.6 Soil Conservation

Soil conservation is the measure of protecting the top most layer (0–20 cm.) of the *soil from natural or induced hazards* (acidification, salinization or other chemical *soil* contamination, erosion, etc.). Soil conservation is associated with crop rotation, cover crops, conservation tillage and planted windbreaks. Unsustainable subsistence of farming and deforestation, loss of soil nutrients, erosion on a massive scale are some causes for addressing the need of soil conservation that protect the soil from being washed away.

36.6.1 Methods of Soil Conservation

Soil conservation is one of the important issues on modern system of agriculture which requires due attention from all corners. Some of the interventions on soil conservation are appended below:

36.6.1.1 Contour Ploughing and Terrace Farming

Contour ploughing involves ploughing grooves into the desired farmland, then planting the crop in the grooves following the contours. It a very effective way of farmland on slopes to prevent runoff and erosion and to improve crop yields. Terracing is a method of carving multiple, flat levelled areas into hills. Steps are formed by the terraces, which are surrounded by a mud wall to prevent runoff and hold the soil to preserve nutrients.

36.6.1.2 Runoff Control at the Boundary

Planting trees, shrubs and ground cover around the perimeter of farmland, which impedes surface flows and helps keep nutrients in soil is another way of control.

Using the grass way is a specialized way of handling perimeter runoff that uses surface friction to channel and dissipate runoff.

36.6.1.3 Windbreaks

Rows of tall trees are used in dense patterns around the farmland and prevent wind erosion and provide year-round protection.

36.6.1.4 Cover Crops/Crop Rotation

Cover crops are rotated with cash crops to blanket the soil all year-round and produce green manure that replenishes nitrogen and other essential critical nutrients. Using cover crops can also suppress weeds infestation.

36.6.1.5 Tree Plantation Programme

Reforestation is the name given to the process by which new crops or plants are planted in an area that once used to bear foliage but now has none. Reforestation brings a piece of land back to life and thus restores resilience of soil in a particular area. Afforestation, on the other hand, is the process by which new crops or plants are planted on a piece of land that had previously been barren.

36.6.1.6 Soil Salinity Problems

Due to deposition of salt in soil surface, salinity is developed. Using humus can prevent this or growing salt tolerant crops to rejuvenate the soils and replace loss of nutrients.

36.6.1.7 Use of Chemical Fertilizers

Proper and required amounts of the correct chemical fertilizers are to be added to the soil as and when required. Addition of an excess of chemicals leads to the soil toxic rather than keeping it healthy.

36.6.1.8 The Soil Microorganisms

The earthworms and other good microorganisms in the soil can keep it healthy. Their population in the soil can easily be enhanced by planting trees and growing crops or also by using the right type of manures and fertilizers in soils.

36.7 Water Conservation

The unnecessary use of water is reduced to improve the water use efficiency (WUE) as because fresh clean water is a limited resource, as well as a costly one. Every individual depends on water for livelihood and hence supply of water should be pure and away from pollution. Judicious use of water puts less weight on our sewage treatment facilities which use an ample amount of energy for heating water. For the past 50 years, the extraction of fresh water from icebergs has expanded because of the growing progression in the life processes where a more significant amount of water is needed. By conserving water may reduce the soil immersion by lessening contamination and overloading municipal sewage flow to lakes and rivers. Even the community-wide domestic water preservation can avoid the expensive sewage system development.

36.7.1 Water Conservation in Agriculture

Water saving irrigation system practices in the agriculture is linked with the chisel plow aeration of compacted soils, furrow digging and levelling of the land surface. Considering the groundwater reserve during the lean period, the low water requiring crops (pulses, vegetables, etc.) should be included in the cropping system.

36.7.1.1 Irrigation Management

Periodical monitoring of soil and water conditions and gathering data on water use efficiency is required. The estimating rainfall, determining soil moisture levels, checking pumping plant productivity and scheduling water systems are some of the techniques. The expansion of drop tubes to a centre pivot water system, upgrading wells with smaller pumps and additionally building a tail-water or return flow recovery system may be taken into consideration.

36.7.1.2 Irrigation Scheduling.

Scheduling of irrigation can lessen the amount of water needed to irrigate a crop successfully by decreasing evaporation losses to provide water for the irrigated plants. The rate and timing of the irrigation can help farmers with more crop yields with less water. In settling on scheduling choices, the followings are to be considered:

- The unpredictable rainfall and the timing of crop water demands.
- The restricted water storage capacity of irrigated soils.
- The limited pumping facilities in most irrigation systems.
- The cost of extra operators in increased water demand.

36.7.1.3 Waste Water Recycling

The use of fresh or deionized water by eliminating contaminants can usually be reused after its first use. Similar processes is needed to create deionized water from municipal water, which likewise would bring about an overall water saving. The used up wastewater might totally be worthy for washing vehicles or the factory premises.

36.7.1.4 Water Recirculation in a Cooling System

Water use inside a recirculating cooling system can significantly lessen water usage by using similar water to play out a few cooling activities. The water savings are adequately significant to bring about a general cost saving to industry. The cooling water protection approaches are ordinarily used to diminish water consumption: evaporative cooling, ozonation and heat exchange.

36.7.1.5 Industrial and Commercial Use of Water

Water recycling is the reuse of water for a similar application for which it was initially used for. Recycled water may require treatment before it tends to be reused. Cooling water distribution and washwater recycling are the most broadly used water recycling practices. The accompanying rules are to be used while considering water reuse and recycling in industrial and commercial applications:

- Possibilities of reuse of water.
- Determination of the base water amount required for the given use.
- Identifying wastewater sources fulfilling the water quality.
- Determination of mechanisms of water shipment for reuse.

36.7.1.6 Other Strategies Include

Rainwater Harvesting

Rainwater harvesting is essentially a technique to store water and for further use. The system has unique units incorporating transportation of rainwater, filtration and storing of the processed water. The storing unit may be made in our homes to spare more water. Some of the methods are as follows:

- Rooftop rainwater storing .
- Traditional water harvesting structures .
- Micro-catchment water harvesting
- Recharging wells, ponds, etc.

Natural and Artificial Regeneration of Vegetation

Regeneration is the renewal of a forest crop by natural or artificial means. More emphasis are to be given on restoration of vegetation on earth.

Water for Sustainable Use

Sustainable water supply includes an arrangement to be extended jointly through the administrative regulation and had applicable to guarantee the sustainability of the system. The major thrust should be given to

- Optimize domestic water consumption.
- Recycle the wastewater/washwater.
- Improvize irrigation methods for improving WUE.

Quality of Water

Water quality is an important factor to address the activities like drinking, swimming or business purposes. It requires collection and treatment of wastewater effluentsand periodical monitoring of pollution.

Awareness Campaign

To maintain sustainable life processes, the need for conserving the good quality water is to be ascertained through spreading awareness/training programme in the community.

36.8 Soil Health and Water Quality

A healthy soil and quality water are of prime importance for the sustainable production system in agriculture. Soil health is defined as the continued capacity of *soil* to function as a vital living ecosystem that sustains plants, animals and humans. The importance of managing *soils* is required for future generations. Healthy soil is full of organisms that turn dead matter and minerals into vital plant nutrients. Healthy soils can absorb and store water as well as can absorb nutrients for the growth and yield of the plants. The balance among organisms within a soil and between soil organisms and their environment is to be associated.

36.8.1 Soil Quality Indicators

Measuring soil quality in identifying soil properties is responsive to management, affects or correlates with environmental outcomes and is capable of being precisely measured within certain technical and economic constraints. Soil quality indicators may be qualitative (e.g. drainage) or quantitative (infiltration rate). There should be a strong linkage between the soil quality indicators and life processes which will correlate well with ecosystem processes, integrate soil physical, chemical and biological properties and processes, be accessible to many users, be sensitive to management and climate, be components of existing databases and be interpretable.

There are three main categories of soil indicators: chemical, physical and biological (Doran and Perkin 1996). Soil quality should have to integrate all three types of indicators (Table 36.2).

Organic matter or more specifically soil carbon plays an important role while transcending all three indicator categories and has influence on soil quality. Organic matter is tied to all soil functions. It affects other indicators, such as aggregate stability (physical), nutrient retention and availability (chemical) and nutrient cycling (biological) and is itself an indicator of soil quality. The indicators can be used in the field as a part of a health card. Some examples of indicators that fall into the three broad categories of chemical, physical and biological are given below:

Table 36.2 Relationship between indicator type and soil function

Indicator category	Related soil function
Chemical	Nutrient cycling, water retention, buffering capacity of soil
Physical	Physical stability, water retention
Biological	Biodiversity, nutrient cycling, filtering

36.8.1.1 Indicator Categories

Chemical indicators can give information about the equilibrium between soil solution (soil-water and nutrients) and exchange sites (clay particles, organic matter), plant health, the nutritional requirements of plant and soil animal communities and levels of soil contaminants and their availability for uptake by animals and plants. Indicators include measures of EC, pH, available N, P, K, organic carbon of soil.

Physical indicators provide information such as water entry and retention that influences availability to plants. Some indicators are related to nutrient availability by their influence on rooting volume and aeration status. The indicator for soil erosion may be depicted as:

- Aggregate Stability
- Available Water Capacity
- Bulk Density
- Infiltration
- Soil Crusts
- Soil Structure and soil pores

Biological indicators provide us about the organisms that form the soil food web responsible for decomposition of organic matter and nutrient cycling. The organisms, both individuals and species, indicate a soil's ability to function or rejuvenate back after disturbance (resistance and resilience). Indicators include measures of:

- Earthworms' activities.
- Particulate Organic Matter (POM).
- Potentially Mineralizable Nitrogen.
- Respiration
- Soil Enzymes
- Total Organic Carbon

36.8.2 Water Quality

Water quality involves the suitability of water for a particular purpose such as drinking or irrigation having chemical, physical and biological characteristics which can be tested or monitored based on the desired water parameters of concern. Water quality includes temperature, dissolved oxygen, pH, conductivity and turbidity as a routine test. The type and quantity of dissolved salts are important indicators affecting water quality. Salts which are originating from the dissolution of lime, gypsum and other slowly dissolved soil minerals are carried with the water during irrigation and remain behind in the soil as water evaporates or is used up by the crop.

The type of salts present in the irrigation water can develop problems as the total salt content increases and for which special management practices may be required to maintain desired crop yields. The suitability for water use is determined by the conditions of use which affect the accumulation of the water constituents and which may restrict crop yield. The soil problems commonly encountered and used as a basis to evaluate water quality are related to salinity, water infiltration rate, toxicity, etc. to name a few.

36.8.2.1 Problems in Irrigated Agriculture

1. Salinity.
   The soluble salts concentration (carbonate, bicarbonate, sulphate, chloride, etc.) in soil or water reduces water availability to the crop and thus yield is affected.
2. Water Infiltration.
   Presence of high sodium or low calcium concentration in soil or water reduces the rate at which irrigation water enters for which sufficient water cannot be infiltrated to supply the crop adequately from one irrigation to the next.
3. Ion toxicity.
   The ions like sulphate, bicarbonate, sodium, chloride or boron from soil or water when being accumulated in a sensitive crop to concentrations high enough may cause crop damage and reduce yields. Excessive uptake of nutrients sometimes reduces yield or quality of the crop for deposits of ions on economic produce or foliage.

36.9 Soil and Water Conservation Policy

Activities on soil and water conservation in general are taken up for reducing the erosion of soil and enhancing the water conservation and distribution, afforestation. The core group was constituted by the National Academy of Agricultural Sciences (NAAS) in 2018 for preparing a National Soil and Land Use Policy at the behest of the Ministry of Agriculture and farmers Welfare, Govt. of India and had meetings with Agricultural Scientists from NARS, representatives from line departments and with progressive farmers. It was felt that there is a need for increasing the area of cultivation to meet the demand of food grain and other agricultural commodities.

The population of the country has reached 1358 million (estimated) in 2018 and is expected to stabilize between 1680 and 1700 million by 2050. In order to resist land degradation and fragmentation of land holdings and protecting the top soil from erosion, building up and maintaining soil fertility and adoption of best and sustainable farm practices in land, the crop and water management are the only pathways for sustainable agriculture, food and nutritional security where a comprehensive National Soil and Land Use Policy and land care practices are needed to enduring sustainable agriculture. The proposed National Soil and Land Use Policy framework envisages that the crop, land and water management are carried out in the best possible scientific manner without any adverse effects/impacts, so that their inherent use potential is handed over as before leading to sustainable land use systems and environment security. Hence, structural reforms, operational interventions and regulations are essential for initiating and strengthening action plans by the stakeholders.

The Ministry of Water Resources, Government of India, in its National water policy has planned for development of water resources and their optimum utilization and has been able to create live water storage capacity of about 253 billion cubic meter (BCM) so far. Conserving water resources is an issue in the event of a need to be addressed on the basis of groundwater potential and water use efficiency. Among the different sources of water, rainfall, river water, surface pond and lakes and groundwater are part of larger ecological system. There may be natural calamities like flood, drought at a particular cropping season. Even there may be over exploitation of groundwater during the lean period of time when the groundwater recharge is at its minimum. Nonetheless, the growth and expansion of economic activities inevitably lead to increasing demands for water for different purposes. The irrigation potential is estimated to have increased from 19.5 million hectares at the time of independence to about 106 million hectares in the year 2010 and is increasing by 2020 to a sizable amount to meet the food and fibre need of a growing population which is expected to reach a level of around 1620 million by 2050. The drinking water need of people and livestock has also to be envisaged to provide adequate drinking water facilities to entire population in both urban and rural areas. The demand of water in the industry underscores the need for the utmost efficiency in water utilization and a public awareness is to be attenuated for conservation of water. The basic frame work considering the socio-economic issues (Fig. 36.2) for managing water resources in an integrated way can help to identify the gaps for implementation.

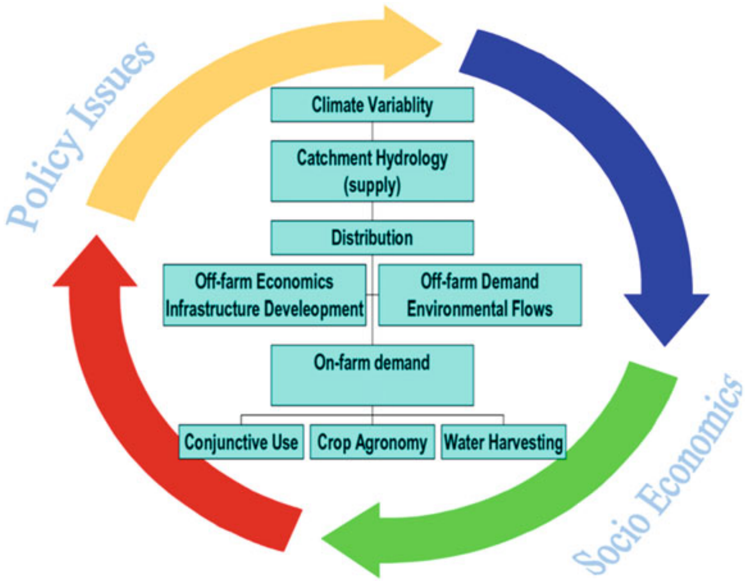

Fig. 36.2 Framework for integrated water resources management at a catchment scale. Abawi et al. (2001)

Rainwater harvesting and its utilization in rice field not only increase the yield but also reduce supplemental irrigation requirement (Mishra et al. 2004) and prevent nutrients' loss through runoff water particularly in medium and lowland situation. During the post-monsoon period, *Rabi* crops may be introduced to increase the cropping intensity by this eco-friendly system.

Besides, the existing strategies and the innovation of new techniques are required to eliminate the pollution of surface and groundwater resources and thus to improve water quality. The science and technology and training would play important role in water resources development in general. The issue related to water pricing, the role of the state as a "facilitator" and "service provider" and that of the private sector in water-related services and Institutional role need to be set up to govern the responsible use of water and also of its conservation and reuse. The interest of the farmers is to be given prime importance while understanding the redistribution of water within the state or across the state of a country.

36.10 Epilogue

Soil and water are the most precious natural resources on earth which require due care from all corners at the National and International level. The different types of soils having different characteristics at the specific agro-ecological region has made the land unique, based on that, planning in agricultural packages and practices are developed. There is diversity in food habit of the people which prioritizes of growing crops in a region. Still there is problems for overusing or underutilizing the available groundwater for irrigation, domestic or industrial sectors causing natural imbalances in the groundwater reserve. The mining of nutrients, soil erosion or nutrient loss from the fertile top soil layer are to be taken care of for sustainable production system. The water harvesting structure to preserve rainwater or even groundwater for its subsequent use during the lean period (Jan-May) will fulfil the domestic as well as for agricultural purpose although the role varies as per the climatic condition of the region which in turn reduces the instability in yield and provides cushion to subsistence level agriculture against the vagaries of rainfall. Hence, the policy and planning on soil and water management should be on region-specific diversified farming system that would ensure increasing land and water productivity, cropping intensity, improving the socio-economic condition, employment opportunity and environmental security as well.

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Soil and Water Management in India: Challenges and Opportunities

37

S. K. Chaudhari

Abstract

Management of natural resources in India has been a challenge whose extent has ascended manifolds over the past few decades owing to a variety of grounds, notably the rising demands and mounting environmental degradation. This review outlines the main challenges that India faces in managing its natural resources. Due to an incredible demographic stress on limited land and water resources, soil and water use deserves special attention. The paper in brief describes how technological interventions, participatory approach and sound policies could improve management of natural resources on priority basis. It then proceeds to outline and highlight some of the increasing challenges of climate change on soil and water complexes. It concludes by signifying several areas of reform that could bring mutual reimbursement across India's productive sectors and future research advocacy to create a more sustainable future.

Keywords

Soil resources · Water resources · Climate change · Sustainable development · Governance

37.1 Introduction

Sustainable agriculture involves efficient management of natural resources to satisfy human needs and maintaining and improving environmental quality and conserving natural resources for future generations. Soil and water are two vital resources for

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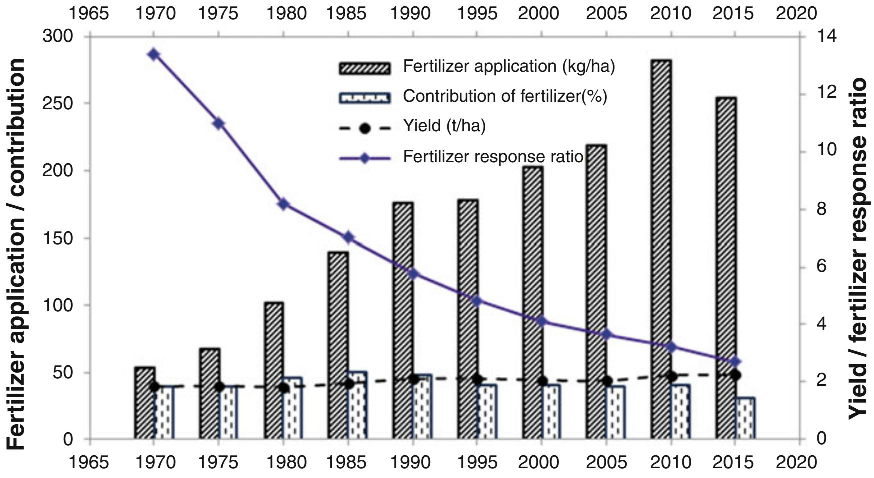
agricultural development and sustaining life on the earth. About 52% of the Indian population depends on agriculture for their livelihood. India presently supports 18% of the world's human and 15% livestock population with only 2.4% of the land mass and 4.2% fresh water resource. With increase in population from 361 million in 1951 to 1.21 billion in 2011, there is tremendous demographic pressure on finite land and water resources. This has resulted in sharp decrease in per capita availability of agriculture land in India from 0.48 ha in 1951 to 0.13 in 2011 and projected to decrease to 0.08 in 2035. Similarly, per capita annual water availability has declined from 5177 m^3 in 1951 to 1614 m^3 in 2011 and further projected to be around 1154 m^3 by 2050 (Jain 2011). Consequently, the share of agriculture sector in total water use is expected to reduce, warranting improved management of this vital resource for sustaining agricultural production in the country.

Though intensive use of Soil and Water resources are inevitable to meet food and nutritional security of the nation, but post-Green revolution, there are concerns about sustainability arising from the decline in soil chemical, physical and biological health due to imbalance use of fertilizer, low addition of organic manure and soil degradation. The imbalanced fertilizer use in terms of NPK is evidenced by their wider consumption ratios of against a desirable in agriculturally important states of Telangana, Andhra Pradesh., Punjab and Haryana. The organic carbon content of the Indian soil is low to very low and deficiency of N is widespread. Deficiencies of P, K, S, Zn and B are increasing in alarming rate. The limiting nutrients do not allow the full expression of other nutrients, thereby, lowering the fertilizer responses and crop productivity. The fertilizer response ratio (kg grain per kg nutrient) decreased nearly by four times (from 13.4 in 1970 to around 3.2 in 2010) in irrigated areas of the country (Chaudhari et al. 2015). While only 54 kg fertilizer nutrients were required per ha during 1970 to maintain the yield level around 2.0 t ha^{-1}, over five times fertilizer nutrients (280 kg) is required presently to sustain the same yield level (Fig. 37.1).

As per the latest estimates (NAAS 2010) based on harmonized database, around 120.4 million ha (36.5% of the total geographical area) of the country is affected by various kinds of land degradation comprising of water erosion (82.6 million ha), wind erosion (12.0 million ha), chemical degradation (24.8 million ha) and physical degradation (1.0 million ha). Out of total degraded area, 104.2 million ha is arable land. Erosion induced loss in crop production in rainfed areas under major cereal, oilseed and pulse crops has been estimated as 13.4 million tons (~16%), which in economic terms is equivalent to 162.8 billion. Besides, over 5.3 billion tons of soil is lost annually through water erosion resulting in a loss of ~8 million tons of plant nutrients (NPK). Similarly, the crop production loss due to salinity and alkalinity at the national level has been estimated to be 5.66 and 11.18 million tonnes, respectively. In economic terms, this is equivalent to the annual monetary loss of 80,000 million and *84th Annual Convention of Indian Society of Soil Science* 1,50,000 million due to salinity and alkalinity problems, respectively, assuming 2014–15 as base year (ICAR-CSSRI 2016a, b).

Similarly, unplanned development and management of water resources has resulted in many negative environmental consequences such as waterlogging and salinity in many canal command, long-term decline in groundwater levels,



Source: *Chaudhari et al. 2018.*

Fig. 37.1 Response and contribution of fertilizer in foodgrain production in irrigated areas over the years in India

deterioration of groundwater quality, seawater intrusion in coastal areas, drying up of wet lands and low-flows in streams, etc. The growing gap between Irrigation Potential Created (IPC) and Irrigation Potential Utilized (IPU) and low overall irrigation efficiency (around 38%) of the major and medium irrigation projects are the major cause of concerns. Further, the anticipated impact of climatic change and climate variability with frequent occurrence of extreme events such as drought and floods may further worsen the water scarcity situation and also deteriorate soil health and quality, affecting agricultural productivity. Hence, a sustainable integrated soil and water resource management aiming at maximizing agricultural land and water productivity is essential. Accordingly, the Government of India took policy decisions and launched appropriate schemes/programmes time to time for sustainable management and utilization of soil and water resources in agriculture. This present paper is an overview of Government's intervention in this direction.

37.2 Enabling Policies of Soil Management in India

The Indian Council of Agricultural Research (ICAR) through the Indian Institute of Soil Science (IISS) and All India Coordinated Research Projects (AICRPs) on Soil Test Crop Response (STCR), Micro- and Secondary Nutrients and Pollutant Elements (MSNP) and Plants, Long-Term Fertilizer Experiments (LTFE) and Network Project on Soil Biodiversity-Biofertilizers are addressing researchable issues related to soil fertility and fertilizer use in the country. The following technologies have been developed by ICAR to promote Integrated Nutrient Management (INM) in the country.

Soil Test Kits The council has developed two portable soil test kits, namely mini-lab (*Mridaparikshak*) by IISS Bhopal and STFR (Soil test and Fertilizer recommendation) metre by Indian Agricultural Research Institute (IARI) New Delhi to supplement soil testing service in the country. The kits are useful in analysing soil samples for the purpose of distributing soil health cards to farmers along with fertilizer recommendations.

Geo-Referenced Soil Fertility Maps The geo-referenced soil fertility maps developed are useful for monitoring and evaluation of soil fertility as well as for making fertilizer recommendations ensuring balanced fertilization and effective distribution of fertilizers in the country.

Integrated Plant Nutrient System (IPNS) IPNS packages incorporating organics, micro and secondary nutrients have been documented for major cropping systems in different agro-climatic regions of the country to promote balanced fertilization. In Indian agro-ecosystems, balanced application of fertilizers and integrated nutrient management can enhance soil carbon sequestration by 20–600 and 100–1200 kg C ha^{-1} $yr.^{-1}$, respectively.

Standardized Vermi/Bio-Enriched Composting Technology In order to promote the use of organic manures in the country, the council has developed technologies to prepare various types of organic manures such as phosphor compost, vermicompost, bio-enriched compost, municipal solid waste compost, etc. from various organic wastes. These organic manures have been tested on different soils using various crops and found useful in improving soil health and crop productivity.

Biofertilizers The Council has also developed improved and efficient strains of biofertilizers specific to different crops and soil types under Network project on S*oil Biodiversity-Biofertilizers*. Liquid Biofertilizer technology with higher shelf-life has also been developed. *Biofertilizers may* increase in productivity by 10%, saving of 20–25% chemical fertilizers, improvement of nutrient use efficiency by 15–25%, produce quality and soil health.

Organic Farming In order to provide technical backstopping for promotion of organic farming in the country, Indian Council of Agricultural Research through its Plan Scheme "Network Project on Organic Farming (NPOF)" is undertaking research to develop location specific organic farming package of practices for crops and cropping systems. Presently, the project is being implemented in 20 centres covering 16 states. Organic farming package of practices for 42 crops/cropping systems have been developed to provide technical backstopping. Suitable varieties of many cereals, oilseeds, vegetables and spices for organic management have been identified. ICAR has recently established National Organic Farming Research

Institute (NOFRI) at Tadong, Gangtok (Sikkim). Further, a Network Project on Organic Farming of Horticulture Crops is also started by ICAR with lead centre at ICAR-Indian Institute of Spices Research, Calicut from 2014.

Resource Conservation Technologies (RCTs) The ICAR has also developed resource conservation technologies (zero tillage, laser levelling, bed planting, SRI, etc.) to save water, nutrient, labour and energy. Conservation agriculture is a necessity of Indian agriculture because of the dwindling soil and water resources, declining soil health and rising cost of inputs making agriculture less remunerative.

The Government under the component of soil health management of National Mission on Sustainable Agriculture (NMSA) is promoting soil test based *84th Annual Convention of Indian Society of Soil Science* balanced and integrated nutrient management in the country through setting up/strengthening of soil testing laboratories, establishment of biofertilizer and compost unit, use of micronutrients, trainings and demonstrations. The Govt. of India took a historical policy decision of introduction of Nutrient Based Subsidy (NBS) on N, P, K and Sulphur containing fertilizers with effect from 1st April 2010. Additional subsidy for fertilizers fortified with zinc and boron was paid at the rate of Rs.500 and Rs 300 per tonne, respectively. However, in order to achieve major objectives of NBS policy of ensuring balanced fertilization, urea needs to be brought under Nutrient Based Subsidy scheme. The Government has also introduced the concept of area and crop specific customized fertilizers for balanced application of NPK along with micro and secondary nutrients. Recently, the Department of Fertilizers, Ministry of Chemicals & Fertilizers has declared subsidy on city compost @ ` 1500 per tonne in support of government's *Swachh Bharat Abhiyan*.

Recently, a National Mission on Soil Health Card has been launched to provide soil tested based fertilizer recommendation to all the farmers in the country. Against a target of 253 lakh samples, 184.75 lakh soil samples collected, 87.90 lakh soil samples tested and against target of 1400 lakh Soil Health Cards, 226.99 lakh Soil Health Cards has been distributed as on 28.06.2016. Nearly 2.00 million ha in Indo-Gangetic Plains have been brought under RCTs mainly zero tillage and bed planting through National Food Security Mission (NFSM) and NMSA schemes.

Soil and its living organisms are an integral part of agricultural ecosystems, playing a critical role in improving soil chemical, physical and biological health, ecosystem functions and productivity. Organic manures/compost is an eco-friendly source of carbon providing energy to these organisms which act as the primary driving agents of nutrient cycling, regulating the dynamics of soil organic matter, soil carbon sequestration and greenhouse gas emission, modifying soil physical structure and water regimes, enhancing the amount and efficiency of nutrient acquisition by the vegetation and enhancing plant health. The *Ministry of New and Renewable Energy* is already implementing *National Biogas* and *Manure Management Programme* which is a Central Sector Scheme of *Biogas Technology Development Division of the Ministry* aiming at setting up of *Family Type Biogas Plants* at rural and semi-urban/households level for recycling of rural wastes linking sanitary toilets with biogas plants (http://mnre.gov.in/schemes/decentralized-systems/schems-2/).

Govt. of India through various schemes like National Centre of Organic Farming, National Horticulture Mission is promoting organic farming and thereby improving soil health in the country. Cultivated area under certified organic farming has grown almost 17 fold in last one decade (42,000 ha in 2003–04 to 7.23 lakh ha in 2013–14) covering 27 states. Recently, dedicated schemes, namely *Paramparagat Krishi Vikas Yojana* (PKVY) and Mission Organic Value Chain Development for North Eastern Region (MOVCDNER) under National Mission for Sustainable Agriculture (NMSA) have been launched. This will encourage farmers to adopt eco-friendly concept of cultivation and reduce their dependence on fertilizers and agricultural chemicals to improve yields. Under this programme, organic farming is promoted through adoption of village by Cluster Approach and Participatory Guarantee System (PGS) certification. Each cluster will be 20 ha each and there will be a total clusters of 10,000. In 2015–16, 7186 clusters were sanctioned and ` 226.19 crore released to State Governments out of approved outlay of ` 511.67 crore. (GOI share is 335.05 crore). In 2016–17, remaining 2814 clusters have been sanctioned.

37.3 Enabling Policies of Water Management

Indian Council of Agricultural Research (ICAR) through Indian Institute of Water Management (IIWM), Bhubaneswar, AICRP on Irrigation Water Management and Consortia Research Platform on Water is addressing issues related to judicious use of water ensuring higher crop productivity in the country. ICAR has developed cost effective, location specific scientific technologies, viz., rainwater harvesting and recycling, multiple use of water, conjunctive use of rain, surface and groundwater resources, smart and precision technologies for irrigation and farming practices, optimum irrigation scheduling, resource conservation technologies, development of land drainage and reclamation of problem soils to enhance irrigation water efficiency and water productivity in Indian agriculture.

The National Water Policy −2012 has made several recommendations for conservation, development and improved management of water resources. The Policy has *inter-alia* recommended that an awareness of water as a scarce resource should be fostered. Central Government has also launched the National Water Mission, one of the eight Missions under National Action Plan on Climate Change (NAPCC), aims at conservation of water, minimizing wastage and ensuring its more equitable distribution both across and within States through integrated water resources development and management'. One of the most important goals of the National Water Mission is to improve the efficiency of water use at least by 20% by the year 2017.

Recently the Government of India under the aegis of *Ministry of Jal Shakti* has launched an intensive "*Jal Sanrakshan Abhiyan*" aiming at water conservation in 154 district of India. In the recent past, Ministry of Water Resources, River Development and Ganga Rejuvenation has launched *Jal Kranti Abhiyan* (2015–16 to 2017–18) in order to consolidate water conservation and management in the country

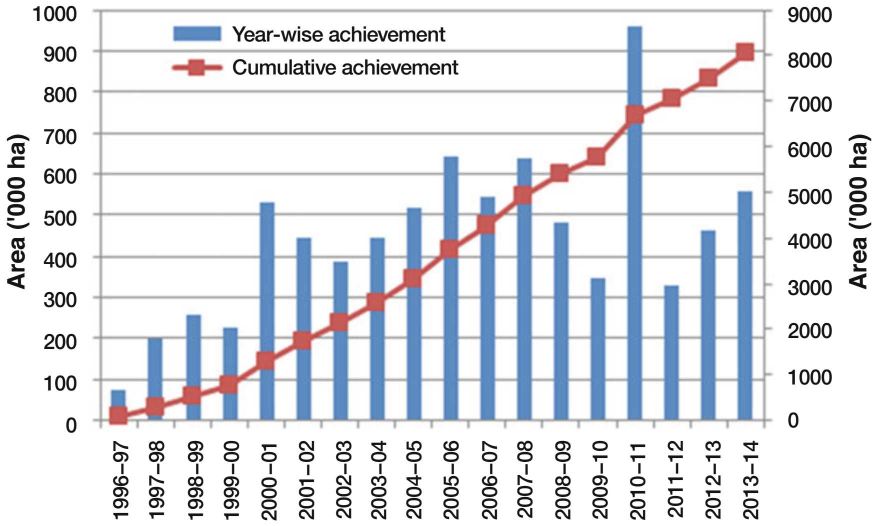


Fig. 37.2 Irrigation potential created under AIBP

through a holistic and integrated approach involving all stakeholders, making it a mass movement. "*Jal Gram Yojana*" component of *Jal Kranti Abhiyan* envisages selection of two villages in every district, preferably being a part of dark block or facing acute water scarcity, as "*Jal Grams*". An integrated water security plan, water conservation, water management and allied activities are envisaged for each of the selected *Jal Grams* to ensure optimum and sustainable utilization of water. The Government is also promoting Participatory Irrigation Management that seeks to involve farmers in the planning and management of irrigation with the purpose of economizing water utilization in irrigation, enhancing systems operations, facilitating equity in water distribution and improving agriculture production in irrigated areas through encouraging collective responsibility for water resource use by farming community. Some of the major programmes in water resources sector are given here under.

Accelerated Irrigation Benefits Programme (AIBP) For development of major and medium irrigation projects in the country, Ministry of Water Resources extends financial assistance to States for completion of identified ongoing irrigation projects. As per present pattern of assistance under AIBP, Ministry of Water Resources is providing grant in the form of Central Loan Assistance for irrigation projects as an incentive to States for creating irrigation infrastructure in the country. AIBP is also providing assistance to irrigation projects under Prime Minister's Package for Agrarian Distressed Districts. Since its inception during 1996–97, total potential created under AIBP by major and medium irrigation projects is 8052.9 thousand hectare up to March 2014 (Fig. 37.2). During the 12th Plan, the AIBP guidelines have been further re-modified and implemented with more emphasis on Command

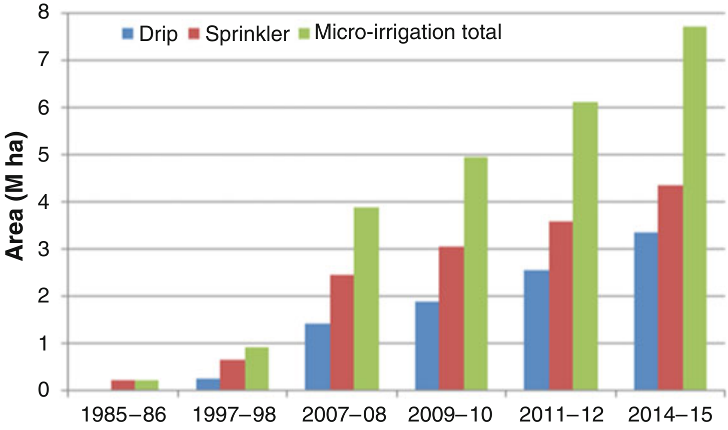
Area Development (CAD) works for the potential utilization. Under PMKSY, 99 ongoing AIBP projects have been identified for completion up to March 2020 in phases. Out of these 23 projects are targeted to be completed by 2016–17, 31 projects by 2017 and rest of the 45 projects by 2019–20.

Command Area Development and Water Management Programme (CADWM) Centrally Sponsored Command Area Development (CAD) Programme was launched in 1974–75 envisages integration of all activities relating to irrigated agriculture in a coordinated manner with multi-disciplinary team under a Command Area Development Authority. The major component of the programme are (1) development of adequate delivery system of irrigation water up to farmers' field with an objective; (2) bridging the gap between potential created and utilized and (3) enhancing water-use efficiency and production and productivity of crops per unit of land and water for improving socio-economic condition of farmers. The programme has been modified from time to time as per requirements felt during its implementation and reclamation of waterlogged areas was added as a component from 01.04.1996. CAD Programme was restructured as Command Area Development and Water Management (CADWM) Programme with effect from 1st April 2004. However, land levelling has been discontinued since March 2004. It also seeks to follow participatory approach and formation of Water Users Association. 219 projects have been completed under CAD programme. Active ongoing projects spread across the 29 States of the country carried over from XI Plan and new projects included during XII Plan as on 31.3.2015 are 142, including 24 new projects included during XII Plan. Since its inception up to March 2013, 20.8 Mha field channels under OFD works and 2.14 Mha field drains have been created under these programmes. An area about 78.278 thousand ha has been reclaimed by these up to March, 2014.

National Project for Repair, Renovation and Restoration (RRR) of Water Bodies Ministry of Water Resources, has initiated a pilot scheme in January, 2005 for Repair, Renovation and Restoration (RRR) of Water Bodies which is directly linked to agriculture. This in a sense addresses multiple objectives such as reclamation of lost irrigation potential, improvement of command area/catchment area of the tanks, restoring/increase in storage capacity of water bodies, recharge of ground water and development of tourism and cultural activities by providing Central Grant to State Governments. The Scheme has been approved for 26 district projects in 15 States, viz., Andhra Pradesh, Bihar, Chhattisgarh, Jharkhand, Karnataka, Madhya Pradesh, Orissa, Rajasthan, Tamil Nadu, West Bengal, Himachal Pradesh, J&K, Gujarat, Kerala and Maharashtra to cover 1098 water bodies with total original culturable command area of 1.72 lakh hectares. After works, an additional irrigation potential of 0.78 lakh hectares is likely to be generated. Physical work for restoration has been completed in 1054 water bodies in 15 States. In XII Plan, the scheme envisages taking up RRR works in 10,000 water bodies (9000 in rural areas and 1000 in urban areas) with an outlay of ` 10,000 crore.

Artificial Recharge to Ground Water through Dug wells A scheme on Artificial Recharge to Ground Water through Dug wells has been initiated during 2007 and is under implementation in 1180 over exploited, critical and semi-critical blocks in 7 States, namely, Andhra Pradesh, Maharashtra, Karnataka, Rajasthan, Tamil Nadu, Gujarat and Madhya Pradesh. Major aim of this scheme is to recharge the existing dug wells using rainfall runoff from the agricultural fields to facilitate improvement in Ground Water situation in the affected areas which in turn will improve the overall irrigated agricultural productivity and help in improving the quality of Ground Water especially in the fluoride affected areas. For benefitting farmers having their own well in their agricultural land, number of irrigation dug wells proposed for recharge is 4.45 million of which 2.72 million are owned by small and marginal farmers. Central Ground Water Board (CGWB) has prepared "Master Plan for Artificial Recharge to Ground Water in India" has been prepared, which envisages construction of different types of Artificial Recharge and Rainwater Harvesting structures in the Country in an area of 9,41,541 Sq. km by harnessing surplus monsoon runoff to augment ground water resources. Special focus is given through Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) for water conservation and water harvesting structures to augment groundwater.

National Mission on Micro-Irrigation (NMMI) With a view to increase the area coverage under micro-irrigation in the country, the Government of India has been implementing centrally sponsored scheme on micro-irrigation since January, 2006, which was upscaled as the National Mission on Micro Irrigation (NMMI) in June, 2010. From 1st April 2014, NMMI was subsumed under the National Mission on Sustainable Agriculture (NMSA) and implemented as "On Farm Water Management" (OFWM). From 1st April 2015, Micro Irrigation component of OFWM has been subsumed with *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY) under the programme component "Per Drop More Crop". Subsidy is provided to the farmers under this scheme for installing Drip and Sprinkler irrigation systems with the funding pattern of 60:40 (all States except North Eastern and Himalayan States) and 90:10 (North Eastern and Himalayan States) shared between Central Govt. and State Govt.. 15% additional assistance is provided to small and marginal farmers for installation of micro-irrigation systems compared to other farmers for area covered under Drought Prone Area Programme (DPAP), Desert Development Programme (DDP) and North Eastern and Himalayan States and 10% for other areas. The micro-irrigation technologies (both drip and sprinkler) are quite popular amongst the farmers and adoption rate is also increasing, particularly in the States of Maharashtra, Gujarat, Andhra Pradesh, Karnataka, Tamil Nadu, Telangana, Rajasthan, Madhya Pradesh, Chhattisgarh and Haryana. Area under micro-irrigation has increased from merely 0.23 M ha in 1985–86 to 7.73 M ha in 2014–15 (Fig. 37.3). As on 8-3-2016, the total area covered under micro-irrigation is 8.15 M ha. In 2015–16, against a target of 5 lakh ha, 5.6 lakh ha has been brought under micro-irrigation. About 56% of the area covered under micro-irrigation systems comes from sprinkler irrigation, while about 44% of the area comes under drip irrigation. Since 2005, area covered under micro-irrigation systems has grown at



Source: *Chaudhari et al. 2018.*

Fig. 37.3 Area under micro-irrigation

a compound annual growth rate of 9.6%. Other than financial assistance, various steps taken by Government for promotion of micro-irrigation include: (1) training and awareness programmes, (2) awareness through print media and radio and TV talks, (3) organization of workshops, seminars and interactive meetings, (4) publicity creation through Exhibitions, Fairs and Kisan Melas, (5) publication of literature and (6) short duration films, etc.

Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) With the objective of enhancing irrigation coverage and improving the delivery system at farm-level, *Pradhan Mantri Krishi Sinchayee Yojana (*PMKSY) has been operationalized from 1st July, 2015. The programme envisages end-to-end solutions in irrigation supply chain, viz., water sources, distribution network and farm-level applications. The objective of PMKSY is to ensure access to efficient delivery and application of water and enhance coverage of irrigation for increasing agricultural production and productivity. The scheme has been formulated by amalgamating ongoing schemes, viz. Accelerated Irrigation Benefit Programme (AIBP) of Ministry of Water Resources, River Development and Ganga Rejuvenation; Integrated Watershed Management Programme (IWMP) of Department of Land Resources and On-Farm Water Management (OFWM) component of National Mission on Sustainable Agriculture (NMSA) of Department of Agriculture, Cooperation and Farmers Welfare. The focus is on improving water-use efficiency at the farm-level and bridging the gap between irrigation potential created and utilization. The main components are:

1. Accelerated Irrigation Benefits Programme (AIBP): focuses on faster completion of ongoing major and medium irrigation, including National projects.
2. PMKSY (*Har Khet Ko Pani*): Its aim is to facilitate and provide assured irrigation supplies to each farm. The schemes include (1) new minor irrigation schemes,

(2) repair, renovation and restoration of water bodies, (3) Command Area Development (CAD), (4) groundwater development in potential areas, (5) diversion schemes from plenty to scarce areas, (6) creating and reviving water tanks, pond, etc.
3. PMKSY (Per Drop More Crop): This component emphasizes to promote micro-irrigation (sprinkle, drip, pivots, rain-guns), efficient water conveyance and application, precision irrigation systems, topping up of input cost beyond MGNREGA permissible limits, secondary storage including canal storages for tail-ends of canals, water lifting devices (like diesel/electric/solar pump sets), extension activities, coordination and management.
4. PMKSY (Watershed): It involves ridge area treatment, drainage line treatment, soil and moisture conservation, water harvesting structure, livelihood support activities and other watershed works.

PMKSY is to be implemented in an area development approach, adopting de-centralized state-level planning, allowing the states to draw their irrigation development plans based on district/blocks plans with a horizon of 5–7 years. A sum of ` 50,000 crore of central share has been provisioned for implementation of the scheme during the next 5 years (2015–16 to 2019–20) with a target to bring 2.5 million hectare under irrigation coverage and 1.5 million ha area under command area development.

Jawaharlal Nehru National Solar Mission and Solar Pumping Programme for Irrigation and Drinking Water under Off Grid and De-centralized Solar Applications: A scheme for solar pumping was initiated in 1992 by Ministry of New and Renewable Energy (MNRE) for commercializing solar pumping systems in India, resulting in installation of nearly 14,000 pump sets.

Post the launch of the Jawaharlal Nehru National Solar Mission (JNNSM) in 2010, this scheme was merged under the mission. Presently, under the "Solar Pumping Programme for Irrigation and Drinking Water under Off Grid and De-centralized Solar Applications", that commences from 2014 to 2015 for a 5 year period, MNRE seeks to install solar pump sets in the country in coordination with Ministry of Agriculture, Ministry of Drinking Water and Sanitation and NABARD. The objectives of the scheme are to develop models for deployment of solar pumps in rural areas and scale up this initiative, utilize the programme to support development activities and improve energy access to rural communities. The scheme aims to facilitate the installation of 1 lakh solar pump sets in 2014–15, envisioning the deployment of at least 10 lakh such pumps by the end of 2020–21.

Not only is the quantity of water, but also the deteriorating water quality is a major driver of water scarcity. Instances of high fluoride in 13 states, arsenic in West Bengal and iron in the north-eastern states, Odisha and other parts of the country have been reported. In West Bengal, arsenic toxicity has been observed as a result of over draft, particularly, more withdrawal of groundwater during lean period for summer paddy irrigation. Arsenic enters the human and animal system mainly through contaminated water and food. Use of arsenic - contaminated groundwater for irrigation in the affected regions has become a serious threat to sustainable agricultural production (mainly rice) and livelihood of the people. The Indian Council of Agricultural Research (ICAR) had taken up research on mitigation options of arsenic problem in the country and advocated the following recommendations like arsenic tolerant rice varieties (Muktashri (IET 21845), IET 1444, Gotrabhog, Nayanmoni and Shatabdi), direct seeded rice using drum seeder and seed drill, conjunctive use of ground and surface water, crop diversification with non-edible and leguminous crops, vermin-compost, FYM, green manuring and micro-nutrients (Zinc sulphate) application. Besides, fruit plants and vegetables with fruit as edible part like brinjal, beans, ladies finger, tomato and agro-forestry have also been recommended. While Ministry of Water Resources, River Development and Ganga Rejuvenation (MoWR, RD&GR) is monitoring arsenic contamination in ground water on real time basis and Department of Agriculture and Cooperation and Farmers' Welfare is providing assistance to arsenic affected states for monitoring of arsenic in soils under RKVY.

37.4 Climate Change Impact on Soil and Water Resource in India

Recognizing possible impact of climate change as a major threat to sustainability agriculture and food security, Indian Council of Agricultural Research (ICAR) has given focus on research to ensure climate resilient cropping systems in participatory farming system mode encompassing livestock, poultry and fisheries through a network project, National Innovations on Climate Resilient Agriculture (NICRA) since 2010–11. It includes multi-pronged strategic research, technology development, capacity building of stakeholders and technology demonstrations at farmer's fields focusing on various climate resilient interventions. These technologies have been compiled in technical bulletin entitled "Smart practices and technologies for climate resilient agriculture" and being demonstrated in 151 most vulnerable districts in the country suffering from climatic aberrations. Besides, Agricultural Contingent Plans for 614 districts covering 25 states have been prepared and uploaded atwww.farmer.gov.in, www.agricoop.nic.in and www.crida.in. Short/medium range weather forecasting for agro-advisories is also being provided.

The risk resilient technologies and practices for climate resilient agriculture are being up scaled up throughout the country under the National Mission for Sustainable Agriculture (NMSA). NMSA is one of the eight Missions under the National Action Plan on Climate Change (NAPCC) and seeks to address issues regarding "Sustainable Agriculture" in the context of risks associated with climate change by devising appropriate adaptation and mitigation strategies for ensuring food security, equitable access to food resources, enhancing livelihood opportunities and contributing to economic stability at the national level. It has four major programme components: (a) Rainfed Area Development (RAD), (b) Soil Health Management (SHM), (c) On-Farm Water Management (OFWM) and (d) Climate Change and Sustainable Agriculture: Monitoring, Modelling and Networking (CCSAMMN). RAD aims at promoting integrated farming system (IFS) with emphasis on multi-cropping, rotational cropping, inter-cropping, mixed-cropping practices with allied activities like horticulture, livestock, fishery, agro-forestry, apiculture, conservation/ promotion of Non-timber forest products (NTFPs), etc. to enable farmers not only in maximizing the farm returns for sustaining livelihood, but also to mitigate the impacts of drought, flood or other extreme weather events. Soil Health Management (SHM), one of the most important intervention of NMSA, aim at promoting location as well as crop specific sustainable soil health management including residue management, organic farming practices by the way of creating and linking soil fertility maps with macro-micro nutrient management, appropriate land use based on land capability, judicious application of fertilizers and minimizing the soil erosion. It promotes Integrated Nutrient Management (INM) through judicious use of chemical fertilizers, including secondary and micro-nutrients, in conjunction with organic manures and biofertilizers, for improving soil health and its productivity. OFWM focusses on enhancing water-use efficiency by promoting appropriate technological interventions like drip and sprinkler technologies, efficient water application and distribution system, creating secondary storage at tail end of canal system to store water when available in abundance (rainy season) or from perennial sources like streams for use during dry periods and drainage development through surface/ sub-surface/bio-drainage system. CCSAMMN component of the NMSA addresses climate change adaptation/mitigation research/pilot/model projects to develop suitable sustainable management practices and integrated farming system models suitable to specific agro-climatic conditions.

Government has also recently approved a new crop Insurance scheme namely *Pradhan Mantri Fasal Bima Yojana* (PMFBY) to replace National Agricultural Insurance Scheme (NAIS) and Modified NAIS (MNAIS) from *Kharif* 2016 season. PMFBY has addressed all the shortcomings in the earlier schemes and would be available to the farmers at very low rates of premium. The farmers will get full insurance cover as there will be no capping of sum insured and consequently the claim amount will not be cut or reduced. This scheme would provide insurance cover for all stages of the crop cycle including post-harvest risks in specified instances. The area coverage would be increased from 23% presently to 50% in 2 years.

37.5 Way Forward

It is a fact that the relationship between soil and water productivity is symbiotic and it is difficult to get the maximum impact of one without the other. Although Government has made provision of various components related to soil and water management under various schemes run by different Ministries, the farmers should have the easy accessibility of those facilities for adoption so as to exploit full potential of land and water resources. The futuristic resource conservation strategies of productivity, profitability, sustainability and competitiveness should be holistic in integrated watershed development approach. In this context, agricultural land use planning, based on the soil characteristics, climate, water availability/irrigation facilities, socio-economic imperatives, etc. is essential. Accordingly, NBSSLUP, Nagpur is developing micro-level (1:10,000 scale) agricultural land use plans at 60 selected blocks covering each of the 60 agro-ecological sub-region of the country to enable farmers to utilize the full potential of their land and water resources choosing the right crop/cropping system suitable for the region. The Bureau has signed MOU with several State Governments, namely Gujarat, Meghalaya, Karnataka and Telangana in this direction. Reforms in major and medium irrigation projects to bridge the gap between potential created and utilized, improved coordination across agencies and active involvement of Water User Associations (WUA) are needed for efficient utilization of the available water resources. In view of the emerging challenges, the focus in watershed management programmes should be on watershed plus approach to foster inclusive growth by converging various production/farming systems and enterprises for livelihoods of landed as well as landless, rights and responsibilities for access to and equitable use of created natural resources, management of common pool resources, management of fringe forest areas, post project sustainability, etc. There is also need for convergence of natural resource related activities of different schemes/components being run by different Government Departments and matching policy decision for effective implementation and fruitful outcome. Besides, greater research and development input is required for the management of pastures, hill and coastal agriculture conserving soil and water resource for improving agricultural productivity of the region.

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Indian Fertiliser Policy: Retrospect and Prospect

38

K. V. Praveen

Abstract

Indian agriculture was traditionally driven by locally available regenerable materials for soil fertilisation. The green revolution targeted to enhance the crop production in the country brought about a sea change in the input complex of the Indian farmers, chemical fertilisers and high yielding varieties becoming the major ones along with irrigation. The government nudged the farmers to use more fertilisers by a series of policies targeted to act at different stages in the fertiliser supply chain. These policies were continuously revised as per the government's interest and the performance of the previous policies. The fertiliser use in most crops and most regions of the country is continuously increasing, driven hugely by the policies. However, the crop response to fertilisers in the recent period is showing a decreasing trend, which is a cause of concern along with the growing imbalance in the use of fertilisers. A complex web of policies, to act at different nodes in the fertiliser production and supply chain, have been framed by the government to overcome this issue. The recent policies are farmed with broader objectives like promoting sustainability in the agricultural system, efficient delivery of fertiliser and the subsidies so that the end beneficiary is identified and benefits transferred without leakage. In this chapter, we track the journey of Indian fertiliser policy regime, assess the current status of fertiliser use, and provide some hints on the prospects and possible policy options considering the food security, sustainability and environmental concerns.

Keywords

Chemical fertiliser · Fertiliser policy · Sustainability · Direct benefit transfer

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38.1 Introduction

Fertilisers are an essential input to agriculture since it bears a direct relationship with food grain production along with other factors like High Yielding Varieties (HYVs), irrigation, access to credit, etc. The fertiliser use by the farmers is directly affected by the crop response, fertiliser cost, price realised by farmers for their produce and the access to fertilisers. About 50–60% of the rise in food grain production during the green revolution is attributed to the fertilisers. The increasing fertiliser consumption and increasing crop yield, thus, mutually promoted each other during the green revolution period and several years after that (Praveen 2014a). However, the crop response to fertilisers in the recent period is showing a decreasing trend, which is a cause of concern to the agriculture sector. The imbalance in the use of fertilisers is said to be responsible for this decreasing trend in crop response. A complex web of policies, to act at different nodes in the fertiliser production and supply chain, have been framed by the government to overcome this issue. The recent policies are framed with broader objectives like promoting sustainability in the agricultural system, efficient delivery of fertiliser and the subsidies so that the end beneficiary is clearly identified and benefits transferred without leakage. Since any policy related to fertiliser have a huge impact on a large number of farmers, especially the small and marginal farmers, as well as the industry, the institutions framing the policies have to be cautious enough so that all stakeholders are benefitted to the extent possible.

38.2 Fertiliser Use in Agriculture

The total fertiliser consumption of India is more than 26.7 million tonnes in the year 2015–16. It is constituted by the consumption of 17.3 million tonnes of nitrogenous, 6.9 million tonnes of phosphatic and 2.4 million tonnes of phosphatic fertilisers. The fertiliser consumption which was 0.06 million tonnes in 1950–51 grew rapidly to reach 2.2 million tonnes in 1970–71, 12.5 million tonnes in 1990–91 and 28.1 million tonnes in 2010–11 before decreasing slightly to the current consumption level. The state-wise fertiliser consumption is given in Table 38.1. The states of Uttar Pradesh, Maharashtra, Madhya Pradesh, Punjab and Karnataka are the leaders in total fertiliser consumption, whereas Haryana, Punjab, Bihar, Telangana and Andhra Pradesh lead in per ha consumption. If we see the farm size wise fertiliser consumption, the marginal farmers use the highest level of fertiliser consumption per ha (188.6 kg), followed by small (130.6), semi-medium (113.6), medium (99.4) and large (84.7) as per the input survey 2011. The share in total fertiliser consumption also follows a similar pattern with marginal farmers having the highest share of 35.8% and large farmers with a share of 5.4%. However, the higher level of fertiliser consumption by the small farmers does not mean that they are well off in comparison to large farmers, but it indicates the input-intensive agricultural practices by them in the quest for better income for livelihood (Praveen et al. 2017). The crops that use a

Table 38.1 State-wise fertiliser consumption 2015–16

State	Fertiliser Consumption (‘000 tonnes)	Fertiliser Consumption per ha (kg)	State	Fertiliser Consumption (‘000 tonnes)	Fertiliser Consumption per ha (kg)
Uttar Pradesh	4230.09	163.35	Telangana	1316.25	209.33
Maharashtra	2724.58	116.79	Tamil Nadu	1144.36	194.06
Madhya Pradesh	1966.54	81.78	Chhattisgarh	637.63	111.90
Punjab	1943.71	247.67	Odisha	519.70	100.56
Karnataka	1779.76	145.09	Assam	242.62	59.18
Andhra Pradesh	1698.15	208.93	Kerala	228.63	87.36
Bihar	1696.85	223.86	Uttarakhand	201.18	183.06
Haryana	1647.40	254.58	Jharkhand	169.26	101.23
West Bengal	1615.66	167.98	Jammu & Kashmir	122.25	105.84
Rajasthan	1530.64	58.60	Himachal Pradesh	56.24	59.64
Gujarat	1516.75	121.47	All India	26752.60	133.19

Source: Fertiliser Association of India 2017

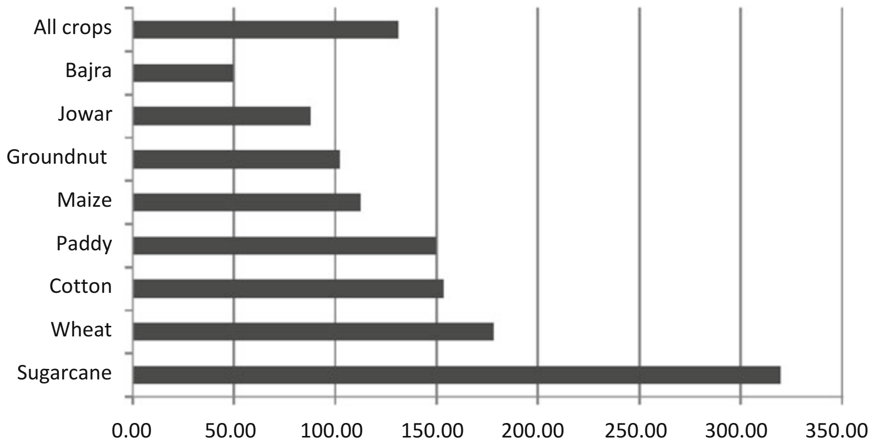

Fig. 38.1 Fertiliser consumption per ha gross cropped area in kg (2011–12)

higher level of fertilisers in India are sugarcane, wheat, cotton, paddy and maize (Fig. 38.1).

Along with the use of fertilisers comes the issue of imbalance in soil nutrients (N:P:K), which is a cause of concern for Indian agriculture. Despite several policy measures by the government like nutrient based pricing and nutrient based subsidy, the soil nutrient balance could not be improved. Evidence also suggests that the policies like decontrolling of P and K fertilisers resulted in a price hike and the farmers started using lesser P and K and more urea. This has worsened the nutrient balance in some of the states. For example, the N:P:K ratio in Rajasthan worsened from 31.2:12.2:1 in the year 2005–06 to 58.2:24.1:1 in 2015–16 (Table 38.2). Similar are the cases of Haryana and Punjab. On the other extreme, there are some states like Kerala and Assam, which use N fertiliser very less than the optimum quantity suggested. The policy dilemma of the government in promoting organic farming for better soil quality on one side and continuing heavy subsidisation of urea and the decontrol of P and K price simultaneously is a hurdle in improving the nutrient balance.

38.3 Indian Fertiliser Policy Regime

Fertilisers play a key role in the performance of the agriculture sector in India. In fact, fertilisers, along with high yielding varieties of crops and better irrigation facilities are credited for the quantum jump achieved in the production of food grains in India during the late 1960s. Having the second largest agricultural land in the world, the prominence of India in the world fertiliser market is decisive. At present India is the second largest producer of nitrogenous fertilisers, after China and third largest in phosphatic fertilisers, after China and the USA. In terms of fertiliser use by countries, India stands tall amongst most. To be specific, the country stands

Table 38.2 Soil nutrient balance in India (selected states)

	2005–06		2010–11			2015–16			2016–17 (P)			
State	N	P_2O_5	K_2O N		P_2O_5	K_2O NP_2O_5			K_2O NP_2O_5			K_2O
Rajasthan	31.2	12.2	1	34.9	15.9	1	58.2	24.1	1	63.6	21.7	1
Haryana	29.6	8.8	1	27.2	9.8	1	52.6	14.8	1	23.5	6.8	1
Punjab	19.9	5.9	1	26.8	8.5	1	18.6	5.4	1	26.8	7.1	1
Assam	1.9	1.2	1	2	0.6	1	4.2	0.8	1	3.9	0.9	1
Kerala	1.1	0.6	1	1.4	0.7	1	1.5	0.5	1	1.3	0.7	1
All India				4.7	2.3	1	7.2	2.9	1	6.7	2.7	1

second in the consumption of both nitrogenous and phosphatic fertilisers with a global share of 16% and 15%, respectively, and fourth in the consumption of potassic fertilisers with a share of 7%. Fertiliser consumption per hectare of agricultural land of India is 144.4 kg, which is very much higher than the world average. India consumes 93.1 kg of N, 37.3 kg of P_2O_5 and 14.0 kg of K_2O per hectare as per the available statistics.

Despite the role that fertilisers played in transforming India to a food sufficient country from a deficient one, its use has been criticised in the recent years for its adverse impact on the soil as well as human health. Fertilisers now bear the blame for harming the environment through nitrate leaching, eutrophication, distorting soil nutrient balance, heavy metal uptake by crops and many other unintended impacts. In fact, fertiliser use itself is now falsely considered as harmful to the environment by many. Rising subsidy burden on the shoulders of the government along with inequality in subsidy incidence with respect to farm size, crops and regions is another cause of concern.

Time and again, the governments that ruled the country have modified and implemented many policies and strategies to ensure the availability of fertilisers to farmers at affordable prices and at the right time. At times, the policies on fertilisers were also used as a tool for political mileage. The fertiliser policies in India mainly whirl around urea, with which the Indian farmers are heavily obsessed. The policies are thus framed separately for urea and non-urea fertilisers. Even though the fertiliser policies implemented since independence can be applauded for their role in bettering of Indian agriculture, it should be modified/remoulded to suit the present scenario while addressing the concerns.

38.4 Policy Retrospect

The fertiliser production, distribution, imports and access to fertiliser for farmers are closely managed by several policies by the government of India. The fertiliser availability became a major constraint in the implementation of the GMF campaign after the imports were not possible during the Second World War. In the year 1943, the government fixed the fertiliser prices on a no-profit-no-loss basis, which was the first major fertiliser policy in India. Since then fertiliser policies have evolved rapidly to ensure the supply of fertilisers equitably by providing it at an affordable price. The major fertiliser policies implemented in India are presented in Table 38.3.

38.4.1 Policies Regulating Fertiliser Pricing and Subsidies

The starting of the subsidy regime can be said to have happened during the late 1970s with the introduction of the Retention Price Scheme. The government implemented the Retention Price Scheme in 1977 for protecting the fertiliser industry and ensuring minimum farm gate prices. This protectionist policy ensured each production unit a 12% post-tax return on net worth regardless of the age, location,

Table 38.3 Major fertiliser policies in India

Year	Policy
1957	Fertiliser control order (FCO)
1973	The fertilisers movement control order
1977	Retention price scheme (RPS) for nitrogenous fertilisers
1979	Equated freight scheme
1980	Block delivery scheme
1991	Decontrolling of fertiliser prices
2003	New pricing scheme (NPS)
2008	Nutrient based pricing of subsidised fertiliser
2008	Policy for new investments in the urea sector
2010	Nutrient based subsidy (NBS)
2013	New investment policy
2015	Mandatory production of neem coated urea
2015	New urea policy
2016	Aadhaar enabled fertiliser distribution system (DBT)
2017	Goods and service tax in fertilisers
2017	Rationalising the size of urea bag
2018	Revision of dealer/distribution margin of urea sales

technology and cost of production. After this policy, the government intervened in the 1980s through fixed subsidies, equated freight scheme and block delivery scheme. The policies of the 1970s and 1980s resulted in heavy subsidy burden to the centre. Cuts in the fertiliser subsidies were a part of the New Economic Policy instituted in India since 1991. To meet this end, the prices of Ammonium sulphate, Calcium ammonium nitrate and Ammonium chloride were decontrolled with effect from 25th July 1991. The fertiliser prices were also increased by 40% in the same month. Owing to the protests from the farmers, the government tried a Dual Pricing Scheme, from which the marginal farmers' were exempted from the hiked prices. Attempts to liberalise the fertiliser sector continued with the decontrol of the prices, movement and distribution of all the phosphatic and potassic fertilisers. This policy is blamed for increasing the fertiliser (P and K) prices and reducing their consumption. The nitrogen fertilisers, however, still enjoyed the benefits of the Retention Price Scheme.

38.4.2 Policies Regulating Fertiliser Marketing and Distribution

The marketing and distribution policies are implemented to ensure the equity of the fertiliser use by region and farmer categories. The marketing and distribution of fertilisers to the farmers are done by about three lakh fertiliser sale points situated all over India. The sale points, 76% of which are under private traders and 24% under cooperative and other institutional agencies, distribute the fertilisers required by the farmers. The most recent policy under this head is the one that rationalises the size of urea bag by replacing the 50 kg bags with the 45 kg bag with effect from 2017. Policy for reimbursing freight for P and K fertiliser under the Nutrient Based Subsidies was introduced in 2012 (Praveen 2014b).

38.4.3 Policies Regulating Fertiliser Production and Imports

The steadily increasing demand for fertilisers in India could be met only if the production and imports are carefully monitored. Primarily because there exist limitations in the availability of raw materials and feedstock required for production and secondly because the imports depend directly on the changing international trade regulations. The options available in policies related to production thus deals with creating new capacities and capacity expansion in public, private and cooperative sector plants. Modernisation of existing units, a changeover to more efficient feedstocks, joint ventures and long-term off-take arrangements with foreign countries also add to these efforts.

38.4.4 Policies Ensuring Nutrient Balance in Soil

The response of the crops to fertilisers has decreased in India due to indiscriminate use of fertilisers, without considering the actual requirements of the soil. The affection of the farmers in India towards the subsidised nitrogenous fertilisers is the prime cause for the nutrient imbalance. The most important attempt in India to ensure the nutrient balance is the introduction of Nutrient Based Subsidy (NBS) in 2010. The NBS so decided by the government will be converted into subsidy per tonne of the subsidised fertilisers. The decision to neem coat the entire urea distributed in the country is another policy targeted to reduce the urea usage per plot, reduce the nitrogen leaching and to check the diversion of urea towards industrial uses.

38.5 Direct Benefit Transfer of Fertiliser Subsidies

The Direct Cash Transfer scheme of fertiliser subsidies is implemented as the Aadhaar enabled Fertiliser Distribution System (AeFDS). The first step towards AeFDS was taken in the year 2011 when the central government appointed a committee headed by the chairman of Unique Identification Authority of India (UIDAI) to suggest the feasibility in providing fertiliser subsidies to farmers' accounts directly. The committee proposed the introduction of DBT in a span of three phases. Mapping of the fertiliser supply chain using digital facilities was the task to be completed in phase 1. This was accomplished by the department of fertilisers through establishing the digital network of mFMS (Mobile Fertiliser Management System). Phase 2 would initiate the deviation from the existing subsidy payment system. In this phase, the fertiliser retailers (and not the industry) should be paid with the subsidies after the retail sales. In the third and final phase, the subsidy amount will be directly transferred to the bank account of the farmers after fertiliser purchase (Kishore et al. 2013). The currently implemented AeFDS is operating in the second phase of the system suggested by the committee, but with a slight modification. At present, the subsidies are still paid to the fertiliser manufacturers (and not to retailers) after the retail sales.

38.6 Fertiliser Policy: Did it Hit or Missed

Earlier (during the late 1960s and early '70s), when the production enhancement was the sole concern of the country, policies facilitating fertiliser consumption augmentation was very well considered as sufficient. The strategy of synergising the release of input responsive cultivars with subsidised fertilisers worked wonders for India during green revolution period and lifted its position from 'begging bowl condition' to status of 'net food exporter'. However, in the present scenario, for any policy on fertilisers to be successful, it should address more complicated issues. The basis for success of a policy now depends on its ability to support; farmers through better and timely availability, at affordable prices, at nearby locations, in the desired quantity and along with necessary information; manufacturers through better raw material availability, improvement in production technology and necessary industry support; distribution system through easing the movement restrictions along with better credit availability; and the government through reduced subsidy burden. In addition, it should promote crop response, maintain or rather improve the soil nutrient balance and cut off the diversion of fertilisers for non-agricultural uses.

The issues faced by different client categories like farmers, manufacturers, players in the distribution system and government are varied and so the policies implemented at different time periods are targeted to satisfy these client groups. Timely availability at an affordable price is the key problem faced by farmers. Policymakers to date could not successfully implement strategies to improve the fertiliser purchasing power of farmers. Past policies could also be in one sense blamed to have not given incentives to the manufacturers to improve the efficiencies in the production of fertilisers. The decision to *Banaras Hindu University, Varanasi* decontrol phosphatic and potassic fertilisers, still keeping urea under price control, was another major decision which resulted in price distortion in the favour of urea. Institutional set up to ensure the quality of the fertilisers distributed to Indian farmers should be widened. The Nutrient Based Subsidy (NBS) Scheme targeted to improve the soil nutrient balance and reduce the subsidy burden, however, could not bring much improvement. In fact, the nutrient balance worsened after its implementation and subsidy burden continued to increase.

38.7 Future Prospects and Options Available

The biggest concern with regard to the use of fertilisers in India is the harm that it is causing to the soil and water. The future policies should target to effectively integrate the traditional and natural means of ensuring soil fertility along with the chemical fertilisers. Such an integrated approach would improve soil quality and nutrient balance along with reducing damage to nature. The direction was already taken in reaching the optimum N:P:K balance should be continued, but it should also consider the local changes in the N:P:K ratio.

Thus, soil test based nutrient ratio results should be made available to entire cultivable land and the farmers advised to use the right mix of fertilisers (Praveen and Aditya 2016). The price distortion among urea and other fertiliser should also be corrected, but after conducting adequate studies so that the farmers are not affected.

38.7.1 Ensuring Fertiliser Availability on Time

The efficiency of the distribution system needs to be improved so as to make available fertiliser when the farmer needs it. At present, the fertiliser distribution system in the country is dominated by the private sector. Thus, the level of competition at the retailer level will decide the farmers' access to fertilisers. Measures must be taken by the government to regulate the distribution system to avoid cartelisation at the retailer level. The policy direction in this regard should prevent hoarding at fertiliser sale points and impart some elements of e-commerce in fertiliser distribution. Farmers could be given the option to intend the required quantity of fertilisers for the next agricultural season, and a mechanism to deliver those at the nearest sale point or at their doorstep on the date of requirement should be developed. In order to check the hoarding at the wholesaler, retailer as well as sale point level, an effective tracking system, like the one proposed by Indian Farmers' Fertiliser Corporation (IFFCO) using Radio Frequency Identification (RFID) could be made use of. These, not so costly but effective, kind of tracking systems could ensure the monitoring of timely movement of fertiliser bags from factory to field.

38.7.2 Purchasing Power Support

Even if the supply chain of the fertilisers is made very competitive and efficient, a large proportion of the farmers, especially the distressed smallholder ones, will not be able to buy them in required quantity for application in their fields. Indian agriculture is dominated by small and marginal farmers and the resource constraints make them buy less than optimum amount of fertilisers. Options to shift towards targeted voucher programmes from the exclusive subsidy regime should be thought of. We apprehend that shifting from subsidy in one go is not at all feasible in India at any point in time, so phase wise transformation is advisable. The voucher programme, if conceived, should ensure the fertiliser supply to the most vulnerable and deserving smallholders through purchasing power support.

38.7.3 Direct Benefit Transfer

The Government has already made its' intention clear to move completely towards a Direct Cash Transfer (DCT)/Direct Benefit Transfer (DBT) regime in order to reduce the subsidy burden. DBT is already in operation for fertiliser subsidy distribution but its impacts are yet to be studied completely. Aadhaar, the common man identification card which is being issued to every human being living in the country is being used for implementing the direct fertiliser subsidy transfer to the farmers' bank account. However, adequate precautions must be taken so as to prevent the issue of false identity and exclusion of deserving candidates. DBT would, in addition, require better banking services to the farmers living in the countryside. Before implementation, the DBT scheme should take care of complications that may arise in future like the mechanism for market price indexation, regulating the market power of dealers, etc. (Praveen 2017).

38.7.4 Price Parity Among Nutrients

Some of the policies implemented in recent years like decontrolling of P and K fertilisers and NBS scheme have in fact created an unintended impact on fertiliser prices. The present figures on fertiliser prices are distorted favourably towards urea. The farmers also are short of any kind of incentive to use high priced phosphatic and potassic fertilisers. This issue qualifies for immediate attention as it may create long-term repercussion on the soil nutrient balance. Bringing urea under the purview of NBS scheme in a phased manner, together with a commensurate increase in the crop support prices announced by the government could be a feasible and effective strategy. This suggestion, however, is highly sensitive and tons of thought should be given before advancing in this direction.

38.7.5 Policies for Technology Upgradation

In technology terms, the Indian fertiliser industry is considered to be comparable to world standards. Still, there exist several plants which use inefficient feedstocks for the manufacturing of fertilisers. The policy for technology upgradation has to be carefully implemented since the industry will have to face challenges from various fronts in the future. It has to promote sustainable development by investing in technologies that are water, energy and feedstock efficient to meet the expectations of the country. The future technologies of the industry should be safe for the environment. It should also keep a balance between economic needs and financial constraints along with impacting the growth. For this R&D in the fertiliser, sector has to be strengthened and plants of high capacities have to be implemented.

The availability of feedstocks and raw materials will be the major concern for the Indian fertiliser industry in future. It can look for feedstock alternatives like Coal bed methane, Coal gasification technologies and Gas hydrates for urea production. The Coal Bed Methane (CBM) is similar to natural gas and it contains more than 90% methane. The CBM gas can be also utilised as a feedstock for the Ammonia or Urea fertiliser complex. Coal gasification is another viable option for urea production. The abundance of coal and lignite in India and the availability of technologies to reduce the ash content underline its relevance for Indian industry. Though gas hydrates are the other viable future fuel, the technology to exploit the gas hydrate reserves are yet to be developed.

Energy consumption is another area where care needs to be taken. Reduction in energy consumption levels can be achieved by installing plants of very high capacities (as in China) and by using better Catalysts. For these, Research and Development (R&D) in the fertiliser sector needs to be strengthened. At present, 15 fertiliser producers are involved in some kind of R&D activities. Almost all of the R&D centres in fertiliser companies are recognised as in-house R&D centres by the Department of Scientific and Industrial Research, Ministry of Science and Technology (DSIR). The Department of Fertilisers (DOF) also sponsors R&D projects. The public funded institutions in the country are not involved much in the R&D activities for fertilisers in the country, which is a matter of concern.

38.7.6 Enabling Sales in Smaller Volumes

One difficulty that the Indian farmers face is the non-availability of fertilisers in customised packs. The fertilisers should be made available in small packs, which the marginal and small farmers will find useful. A policy in this line is having great implications in future since the fixed subsidy floating price is implemented. It should provide the small and marginal farmers in India, the customised quantity of fertilisers, high yielding seeds of the crops suitable to the area and customised quantity of other inputs like plant protection chemicals along with the directions for use of all these inputs. The existing distribution network for fertilisers and other inputs can be utilised for this. The retailers should, however, perform an improved role (of an extension agent) in advising the farmers about the benefits of and how to use, the starter packs. Sales of fertiliser in smaller volumes along with other inputs have proved successful in several developing countries, however, when bringing it to India we have to consider a large number of farmers to be served. Proper pilot studies are inevitable before actually implementing it at the ground.

38.7.7 Quality Assurance

The quality of fertilisers in India is a subject that has not received the level of attention that it deserves. Deluding through adulteration, misbranding, deliberate manufacture of poor quality stuff, less weight of bags and higher price than mentioned in the label are not uncommon. The quality control system for fertilisers in India comprises of mainly the Central fertiliser quality control and training institutes and its regional laboratories. The capacity of the laboratories is, however, not sufficient to enforce quality in all fertilisers all over the country. Capacity utilisation of many of the laboratories should be improved and proper training for sample collection and testing needs to be given to staff. In addition to this, identified progressive farmers at sub-district or village level should be provided with diagnostic kits with which he can test the fertiliser quality at the nearest sale points. Youth could also be encouraged to set up private fertiliser quality checking laboratories at the village level under government support.

38.8 The Concern of Environmental Cost

There are some externalities associated with intensive fertiliser based agriculture. We are applying excessive nitrogen fertilisers to our agricultural crops, which ultimately pollutes our environment. The atmosphere is polluted by gaseous emissions, leaching losses to water bodies etc. The estimates show that India's N_2O emissions from fertiliser application have grown from 121 Gg in 2005 to 162 Gg in 2016 exhibiting a compounded annual growth rate of 2.69%. The state-level analysis pointed Uttar Pradesh, Andhra Pradesh and Maharashtra to be the leading N_2O emitters. N_2O emission per thousand hectares of gross cropped area was highest from Punjab, Haryana and Uttarakhand. Manufacture of fertiliser also involves the generation of greenhouse gases and the total emission from fertiliser production in India was estimated to be 55.6 million tonnes of CO_2 equivalents. Adopting best management practices in nutrient use is the road to reduce environmental costs. Popularisation of best management practices will ensure the application of right kind of fertilisers at the required quantity on right time. Promotion of traditional and organic substitutes also could be done with an understanding of how much quantity of chemical fertilisers can be substituted by the traditional counterparts without affecting the farmers' income.

38.8.1 Sustainable Way Forward

Sustainability issues need to be addressed while framing fertiliser policies in future. The indiscriminate use of fertilisers, especially nitrogen fertilisers, has worsened the soil nutrient balance in several parts of the country. Farmers should be educated about the benefits of applying the right kind and quantity of fertilisers and the ill effects of indiscriminate application. For this mass, efforts need to be initiated by the government. Soil health cards are now being issued to farmers in many of the states. This is a welcome development since these cards mention the nutrient status of the fields, which needs to be expanded all over the country. Some mechanism should be developed to link fertiliser use with soil health cards. Digital records of these health cards can be used to cross verify whether the right kind of fertilisers is dispatched to each district. Availability of customised and fortified fertilisers should be ensured as per the requirement of the area. The recent decision of the government to neem coat almost the entire urea sold in the country is also a measure showing the intent for drifting towards sustainable use of fertilisers, however, its impact is yet to come. Neem coating of urea will improve the nitrogen use efficiency of crops delaying the nitrogen release to the soil, reduce the nitrate leaching and eutrophication and check the diversion of urea to some extent. More of such speciality fertilisers, for example, slow-release fertilisers like sulphur coated urea, urea deep placement and other area and crop specific and water-soluble fertilisers addressing the secondary and micronutrient deficiencies of the soil should be promoted. Measures to promote biofertilisers are also very important in building a sustainable system. Despite the proven benefits of using biofertilisers, its sales are not picking up in the country. One needs to go deeper into this issue to understand whether the problem exists in the demand side or supply in order to make a positive change.

38.9 Conclusion

Several policies have been attempted by the government of India in the fertiliser sector starting from the 1940s. These timely and effective policies have made India one among the largest producers and consumers of fertiliser in the world. A policy which makes the fertilisers available in smaller quantity along with other inputs like high yielding seeds and plant protection chemicals may better the small and marginal farmers in India. Creating new capacity and modernisation of existing units, a changeover to more efficient feedstocks, joint ventures and long-term off-take arrangements with foreign countries can help in ensuring the availability of fertilisers. The future technologies of the industry should be safe for the environment for which R&D in the fertiliser sector has to be strengthened. A policy to provide fertiliser mix customised to the requirements of the soil in different regions will help to ensure the nutrient balance in Indian soils. Finally, fertiliser subsidies if distributed should be targeted. The problems and fraught involved in the mechanism of Direct Benefit Transfer of fertiliser subsidy should be addressed promptly for harvesting its benefits. Though challenges are many in the fertiliser sector, they can well be addressed with evidence-based policies. While formulating such policies, care must be taken to ensure that the interests of all the stakeholders are not harmed. All it takes on the part of government is iron will and informed policy choices.

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Long-Term Fertilizer Experiments in India: Achievements and Issues for Future Research

39

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Abstract

The long-term fertilizer experiments (LTFE) at fixed sites in different agro-ecological zones (AEZ) covering predominant soils and important cropping systems were conducted to monitor the changes in soil quality, crop productivity, and sustainability due to continuous application of plant nutrient inputs through fertilizers and organic sources. These LTFEs results showed the yield trend in order of NPK + FYM > 150% NPK > 100% NPK + Zn > 100% NPK > 100% NP > 100% N > control at most of the sites. However, in Alfisols of Ranchi, Palampur, and Bangalore continuous application of N alone had deleterious effect on yield and it even could not sustain yield to that of control (no fertilizer and manure). Integrated nutrient management and soil amendments with lime in Alfisols, practicing green manuring and addition of FYM have improved the crop productivity and soil quality as well. These LTFEs across the locations illustrated key findings that balance plant nutrition improved SOC, microbial biomass carbon, and C stock in soil. The balance nutrient management also enhanced nutrient use efficiency across all the cropping systems. It has been further seen that in majority of soils there is accumulation of phosphorus (P) and hence needs a holidaying of P wherever necessary. On the contrary, the continuous absence of potassium (K) in fertilizer schedule necessitates K supplementation to have optimum crop yields. Similarly, in order to meet out the emerging deficiency of micronutrients and Zn in particular integrated nutrient management is of prime importance. The balanced nutrient management to some extent helped in mitigating climate by assimilating more atmospheric CO_2 through photosynthesis and pushing more carbon into soil through C sequestration processes. Thus,

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experiments showed that balanced and integrated nutrient application enhanced crop productivity, soil health, and sustainability. Thus AICRP-LTFE could be used as platform to address the issues such as optimization of nutrient management practices for carbon sequestration, assessment of functional biodiversity, and soil ecosystems service and beside for assessing impact of changing climate on crop productivity and soil health.

Keywords

Soil health · Long-term fertilizer experiments · CARBON sequestration · Nutrient management · Climate change · India

39.1 Introduction

Sustaining soil health is the key to fulfill the three basic human needs of food, fiber, and shelter. In addition to these three basic needs of human, soil performs several functions such as, acts as universal filter for water and air purification, store water and nutrient for plants, habitat of beneficial soil organisms, provide physical support to plant, moderate the climate and helps to sustaining ecological balances by maintain equilibrium of gasses in atmosphere. To meet food and fiber demand of ever increasing population in Indian subcontinent diverted the attention of the researchers and the planner to intensify agriculture by using modern agriculture techniques, uses of high analysis fertilizer and high yielding varieties, irrigation, plant protection measures, etc. Adoption of modern techniques Indian witnessed green revolution, but at the same time it also led to nutrient imbalances, witnessed multi-nutrient deficiencies, decrease in nutrient use efficiencies, partial and total crop productivity which threatened sustainability.

The continuous change in climate, population pressure, land constraints, and ignoring traditional soil management practices have often had adverse effect on soil fertility (Kumwenda et al. 1996). It is often said that Indian agriculture is operating at a negative nutrient balance of about 10 million tons of NPK. This happens when nutrient supplies through external sources are less than nutrient removal by crops from the soil. Negative balances indicated that the soils are being mined and if this continues then farming systems may become unsustainable in the years to come. Under this situation, it has become imperative to maintain supply of the nutrient in sufficient quantity in soil through external source like fertilizers and manure. To enhance and sustain the productivity a need of interventions in soil fertility maintenance program was felt. Since fertilizer has played a key role in increasing agricultural production and its consumption in agriculture is increasing rapidly, so a need is felt for studying the impact of fertilizers not only on the crop yields and quality but also on the soil and environment under intensive cropping systems which is major contributors to food basket. Fertilizers are chemicals and may have effect on functioning of soil. This gave a call for a continuous study at fixed sites for monitoring the soil health with the objectives of developing strategies for sustained productivity by incorporating the intervention.

To have a regular watch on soil health, Indian Council of Agricultural Research decided to launch the "All India Coordinated Research Project on Long-Term Fertilizer Experiments (AICRP-LTFE)" in September 1970 at 11 centers'.

The purpose of conducting long-term fertilizer experiments at fixed sites in different agro-ecological zones (AEZ) with predominant soils and important cropping systems was not only to monitor the changes in soil quality, crop productivity, and sustainability due to continuous application of plant nutrient inputs through fertilizers and organic sources, but also to help in the synthesizing the strategies and policies for rational use and management of fertilizers to improve soil quality and to minimize environment degradation. Thus, the thrust of AICRP is on productivity, sustainability, and environment safety. In this article an attempt has been made to highlight the major achievements emerging from half-a-century data. At the end, future course of action and way forward is envisaged. The work carried out at different centers of LTFE was reviewed by QRT during 1997 and recommended to enlarge the mandate and objectives of the project and changed its title as AICRP on "Long-term fertilizers experiments to study changes in soil quality, crop productivity and sustainability."

39.2 Crop Productivity

To feed burgeoning population in the country it is essential for us to sustain and enhance productivity of crop vis-à-vis decline in availability of natural resources such as land and water. In order to enhance and sustain productivity use of chemical nutrients in integrated manner is essential. The imbalance nutrient application witnessed gradual decline in yield. Results of crop productivity indicated that the nutrients in balance (NPK + Zn) and integrated manner (NPK + organic manure) gave consistently stable yields over the years. The NPK + FYM treatment gave the highest yield compared other treatments. The yield followed the trend of NPK + FYM > 150% NPK > 100% NPK > 1005 NP 100% N > Control (Fig. 39.1) at most of the sites. However, on Alfisols of Ranchi, Palampur, and Bangalore continuous application of N alone had deleterious effects on yield and even could not keep pace with yield of control. Integrated nutrient management and amendments like lime, green manure, and FYM over the years improved the soil fertility and crop productivity on Alfisols, with FYM showing superiority over lime in sustenance the productivity.

Barring a few crops and places, balanced and integrated nutrient management led to continuous increase in productivity with time which could be attributed to increase in soil organic carbon and consequently in soil health.

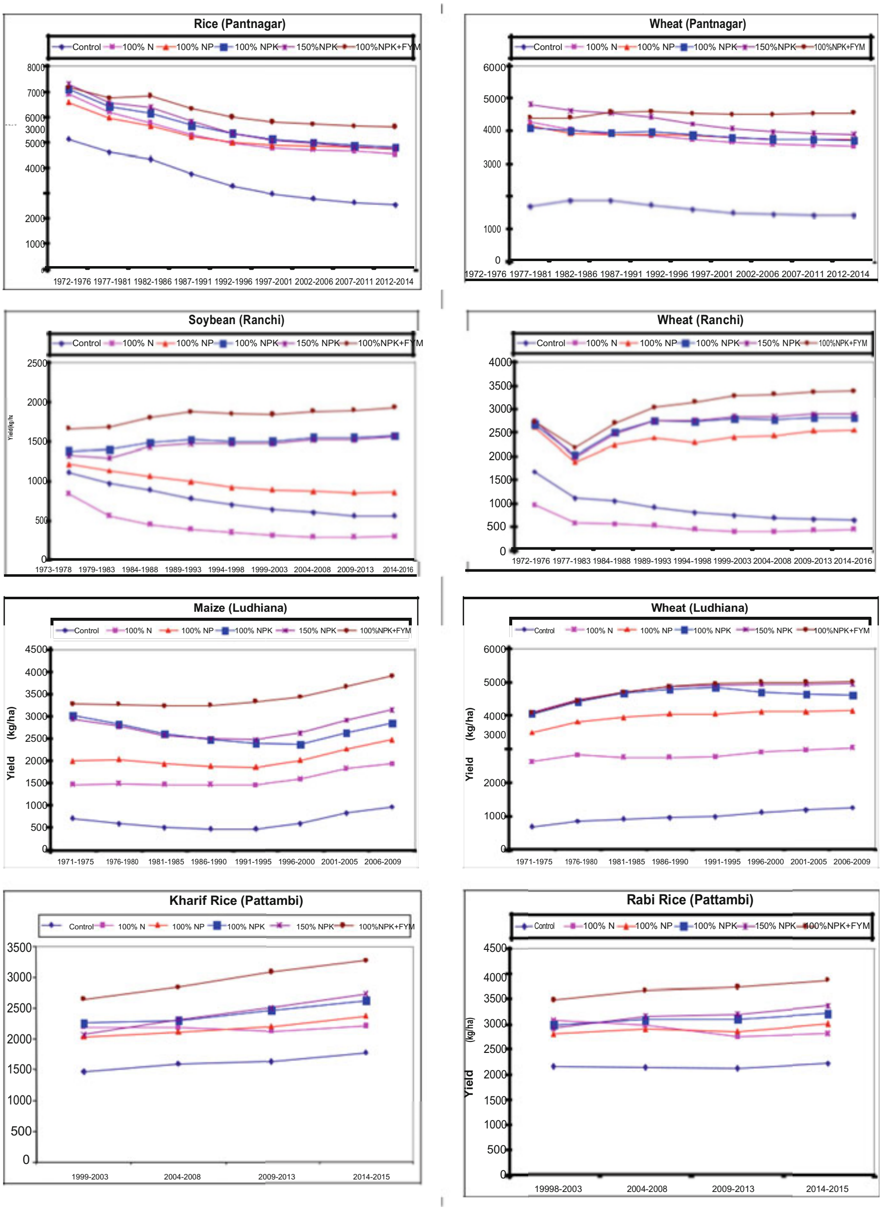

Fig. 39.1 Effect of long-term fertilization on yields (kg ha^{-1}) of different crops at LTFE locations

39.3 Yield Sustainability

Sustainability yield index (SYI) indicates that this much crop productivity would be achieved under worst cum worst situation. Imbalance nutrient application resulted in less SYI values indicating treatments are not sustainable and unfit for continuation (Table 39.1). On the contrary, balance nutrient application resulted in larger SYI values indicated higher sustainable compared to imbalance treatments. The largest SYI was observed on integrated plant nutrient supply (IPNS) across the soil type and cropping systems (Wanjari et al. 2004). Thus, for higher sustainability IPNS could be better option.

39.4 Nutrient Use Efficiency

Perusals of data (Fig. 39.2) revealed that N use efficiency of crops improved considerably with balanced fertilization (NPK). Addition of FYM further increased it. However, in case of Alfisols of Pattambi prolonged wet conditions of soil might be responsible for poor N use efficiency. Phosphorous use efficiency (Fig. 39.2) in crop increased xoxn increased in presence of K. The K use efficiency values were higher compared to N and P (Fig. 39.2). This is due to larger uptake of K than applied. Data further indicated application of FYM resulted in increase in use efficiency of all the three major nutrients in all the crops. Increase in nutrient use efficiency on integration of nutrient is due to increase in crop productivity (Singh et al. 2019).

Table 39.1 Sustainable yield index (SYI) estimates for long-term fertilizer experiments in India

Center	Crop	Control	N	NP	100% NPK	150% NPK	NPK + FYM	NPK + Lime
Barrackpore	Rice	0.15	0.29	0.34	0.35	0.41	0.40	–
	Wheat	0.11	0.30	0.36	0.38	0.47	0.41	–
Pantnagar	Rice	0.13	0.39	0.43	0.41	0.38	0.50	–
	Wheat	0.15	0.46	0.51	0.51	0.50	0.62	–
Ludhiana	Maize	0.03	0.18	0.24	0.29	0.32	0.44	–
	Wheat	0.14	0.43	0.63	0.70	0.76	0.78	–
Palampur	Maize	0.01	0.07	0.15	0.35	0.36	0.53	0.47
	Wheat	0.04	0.05	0.15	0.28	0.28	0.42	0.40
Ranchi	Soybean	0.10	0.01	0.21	0.49	0.47	0.62	0.60
	Wheat	0.03	0.02	0.29	0.35	0.36	0.43	0.41
Jabalpur	Soybean	0.13	0.14	0.26	0.32	0.30	0.35	–
	Wheat	0.14	0.15	0.49	0.54	0.56	0.59	–
Jagtial	Kharif rice	0.32	0.46	0.52	0.55	0.57	0.58	–
	Rabi rice	0.24	0.31	0.45	0.46	0.50	0.48	–

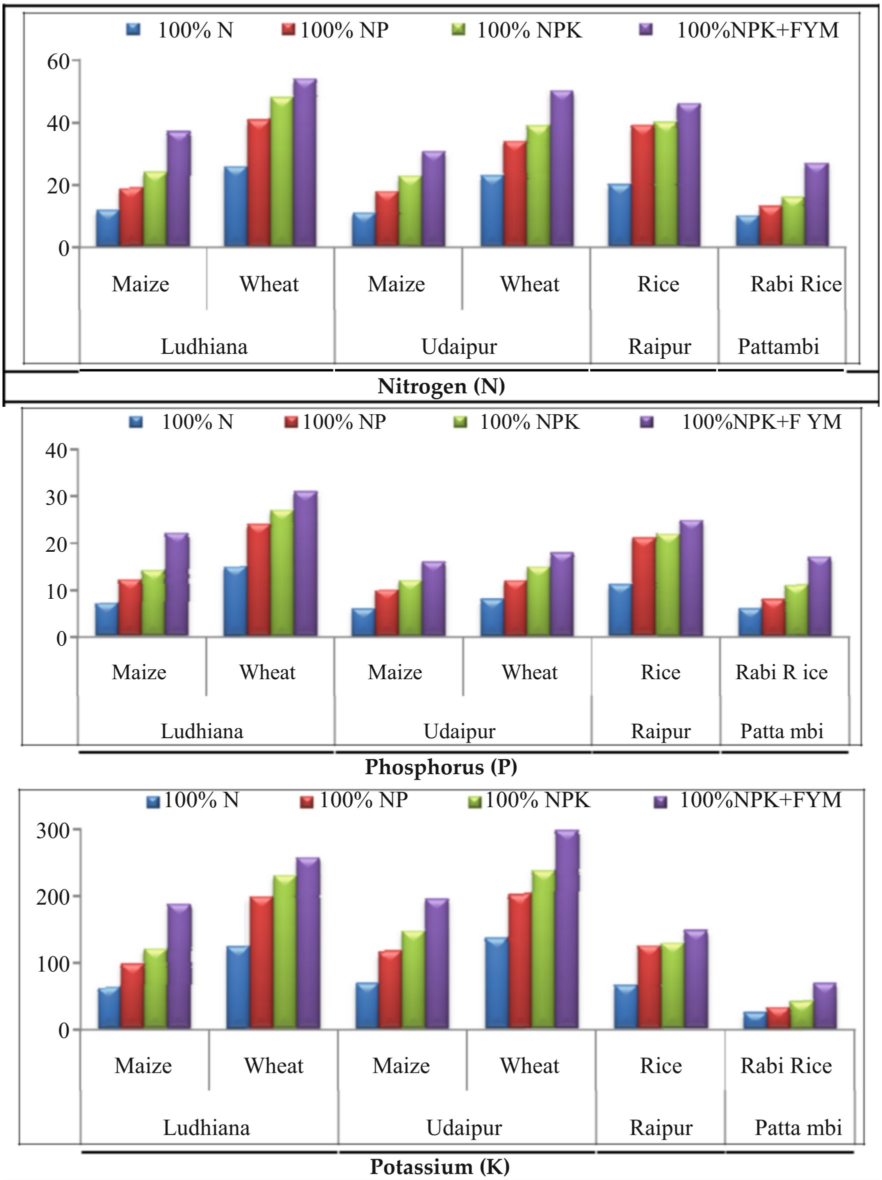

Fig. 39.2 Nutrient use efficiency (%) of N, P, and K in different LTFE locations

39.5 Soil Organic Carbon (SOC)

Soil organic carbon is key constituent for assessing health of any soil. In soil C exists in several pools but in this section emphasis has been given on Walkley black carbon. Since organic carbon is food for the soil organism thus soil carbon plays important role in availability of nutrient to plant. Enhancing the SOC content in soil is essential to improve soil quality, ensuring food security and minimizing environment pollution. Data on SOC (Fig. 39.3) revealed that growing of crops with balanced nutrient management option resulted increase in SOC at all the centers except at Pantnagar (Mollisols). At Pantnagar after decline in SOC to a level, improvement in soil carbon is noticed during last five years under balanced nutrient

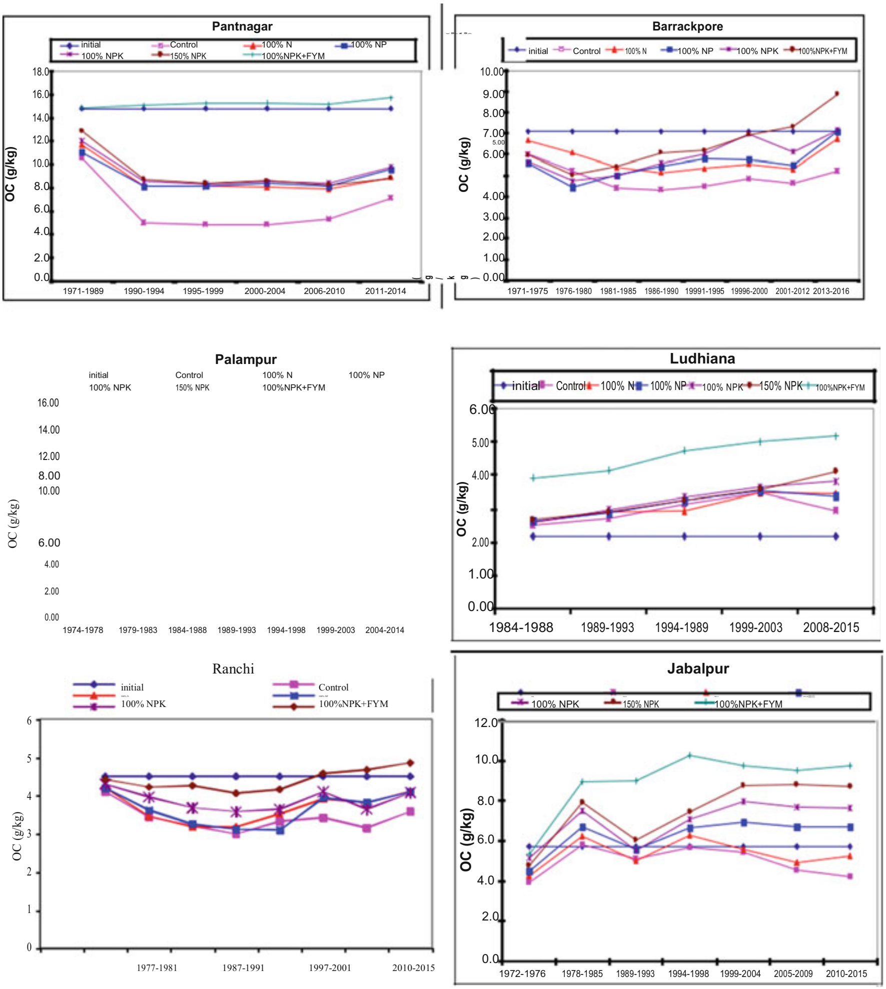

Fig. 39.3 Effect of nutrient management on SOC (g kg^{-1}) at AICRP-LTFE centers

management. The increase in SOC on application of fertilizer is attributed to increase in quantity of residual biomass as a result of higher primary productivity (Grain + straw). Thus, from the data it is clear that balanced application of nutrient through fertilizer did not have any adverse effect on soil carbon rather resulted increase in SOC (Manna et al. 2013) and ruled out that chemical fertilizer deteriorate SOC.

39.6 Available Nutrient (N, P, K, and S) Status in Soil

The available nutrient status has been extensively study during last 46 years including available N, P, K, and S status. Results from LTFE indicated that balanced use of nutrient resulted increase in N content at most of the sites, if not then at least maintained. Cropping system also played a role in maintaining the N status. For example, soybean based cropping system at Jabalpur and Parbhani resulted significant improvement in available N status in all the treatments. The larger N content in residual biomass of soybean and biological fixation of N (Fig. 39.3) are the reasons for increase in soil N status in all treatments. Here, it could be supplemented that at these sites increase in SOC was also in larger quantity. It is found that available N status followed trend similar to SOC. However, at Palampur this relationship is not true in spite of larger SOC, available N status is relatively low compared to other sites. This is probably due to temperate climate conditions which slow down the decomposition of organic matter and maintained wide C: N ratio in soil.

Phosphorous is second nutrient to which crop responses, was observed across the cropping system that regular supply of P to plant is essential to sustain soil productivity. On continuous application of P fertilizers, increase in available P status was recorded. Increase in P status is relatively larger in Alfisols compared to Vertisols of Jabalpur and Akola. Vertisols being calcareous in nature have very high P fixing capacity. Even after 40 years increase in P status in soils of Coimbatore, Jabalpur, and Akola is less compared to alluvial soils of Punjab and Delhi. Incorporation of FYM resulted increase in available P status at all sites. This is due to additional supply of P and secondly application of FYM on decomposition forms organic complex which blocks P fixation sites (Singh et al. 2007).

Potassium is required in large quantity almost equal to N even though it is not constituent of any plant parts. In principle, available K status should decline with time as K removed by crop is always larger than applied but it is not always true. Available K status (Table 39.2) revealed decline in Vertisols and associated soil (Akola, Jabalpur, Junagadh), whereas in Alfisols (Bangalore, Bhubaneshwar, Pattambi) similar trend was also noted but with less magnitude. However, Inceptisols of Ludhiana, New Delhi, and Pantnagar perceptible increase in available K status was noted. At all the three places a good amount K is also added to soil through irrigation water which contains 5–7 ppm K and adds nearly 50–70 kg K ha^{-1} (Singh et al. 2014a).

An increase in available S was recorded compared to initial at almost all sites of LTFE except at Udaipur. It is because even though there is no treatment for S but it is being applied by default through single super phosphate (SSP). At Udaipur, P is

Table 39.2 Effect of nutrient management options on available soil K status (kg ha^{-1}) at different AICRP-LTFE locations

Location	Initial	Control	N	NP	NPK	NPK + FYM
Akola	358	169	204	230	381	490
Jabalpur	370	238	243	250	292	329
Junagadh	184	174	155	160	207	–
Pattambi	173	41	49	41	59	69
Ludhiana	88	81	89	106	134	155
New Delhi	155	187	252	259	315	302
Pantnagar	125	93	89	131	129	145

Table 39.3 Annual input output of N (kg ha^{-1}) in soils of Jabalpur and Ranchi due to soybean

	Atmospheric N fixed by soybean (HBNs)	Net N balance gain by soil	Atmospheric N fixed by soybean (HBNs)	Net N balance gain by soil
Treatment	Ranchi[a]		Jabalpur	
Control	49.7	9.8	62.8	39.7
100% N[a]	–	–	73.1	29.3
100% NP	47.4	2.7	114.5	51.4
100% NPK	136.2	30.9	128.8	66.2
100% NPK + FYM	169.5	36.6	161.1	66.5

Note: N fixed by HBNs = Total N uptake by Soybean × % Ndfa/100 (e.g. in control: 58.2 × 85.5)/100 = 49.7

[a]Because of very poor productivity %Ndfa was negative

supplied through di-ammonium phosphate (DAP) and S is applied through gypsum in one of the treatments. Relatively large amount of S is maintained in Alfisols at Bangalore and Bhubaneshwar may be because of acidic nature of the soil and also presence of sulfate in soil. At Ranchi source of P is DAP, so in all the treatments S is maintained at the same level (Singh et al. 2019).

39.7 Biological N_2-Fixation and Addition to Soil

Data on biological N_2 fixation (Table 39.3) clearly indicated that quantity of N accretion in soil depends on %Ndfa and the productivity of soybean.

Application of nutrient in balanced form resulted in increase in atmospheric N_2 fixation by soybean. Though application of FYM over and above NPK increased accretion of N and biological N_2-fixation by soybean compared to NPK alone. Therefore, biological fixation of N by soybean is dependent on crop productivity. This study clearly indicated that to harness N_2-fixation capacity of soybean, we should grow soybean with balanced nutrition and then we can only offset N derived by soybean from soil through biological fixed N of residual biomass of soybean and would lead positive balance of N in soil (Singh et al. 2014b).

39.8 Apparent P and K Balance

From the data generated on apparent balance of P (Table 39.4) and K (Table 39.5) revealed a positive balance of P in the plot received continuous supply of P, however, negative balance is noted in treatment, did not receive P all through. In case of K data indicated negative balance irrespective of presence or absence of K in fertilizer schedule at most of the experimental sites. In presence of K application, decline in magnitude of negative K balance was less. Positive Balance of P is due to less removal of P by crop compared to quantity of P applied. However, negative balance of K in all the treatments is due to removal of K by crop in larger amount than the quantity of K supplied externally.

39.9 Heavy Metal Status

Even though there is no definite effect of treatment on trend as far as heavy metal status is concerned. However, data from Alfisols of Ranchi revealed little increase in concentration in lead (Pb) which seems to be due to application of P fertilizer

Table 39.4 Apparent phosphorus balance (kg ha^{-1}) in different locations of LTFE

Center	P added	P removed	P balance (kg ha^{-1} year^{-1})
Ranchi			
100% N	0	2.7	−2.7
100% NPK	52	16.4	35.6
Akola			
100% N	0	11.9	−11.9
100% NPK	76	38.6	37.4
Barrackpore			
100% N	0	34.2	−34.2
100% NPK	65	50.7	14.3
Jagtial			
100% N	0	33.9	−33.9
100% NPK	52	47.2	4.8
Ludhiana			
100% N	0	24.8	−24.8
100% NPK	52	37.3	14.7
Jabalpur			
100% N	0	15.63	−15.63
100% NPK	70	28.95	41.05
Pantnagar			
100% N	52	34.4	17.6
Coimbatore			
100% N	0	17.3	−17.3
100% NPK	52	21.9	30.1

Table 39.5 Apparent potassium balance (kg ha^{-1}) in different locations of LTFE

Center	K added	K removed	K balance	K balance (kg ha^{-1} year^{-1})
Jabalpur				
100% NP	0	8668	−8668	−261
100% NPK	2220	9760	−7540	−188
Coimbatore				
100% NP	0	5360	−5360	−134
100% NPK	1760	7280	−5520	−138
Barrackpore				
100% NP	0	7680	−7680	−192
100% NPK	6000	8440	−4440	−111
Pantnagar				
100% NP	2000	7088	−5088	−127
100% NPK	4920	7171	−2251	−56
Bangalore				
100% NP	0	3250	−3250	−130
100% NPK	3100	6500	−3400	−136
Ranchi				
100% NP	0	3400	−3400	−85
100% NPK	2640	6320	−3680	−92
Ludhiana				
100% NP	0	4540	−4540	−113
100% NPK	2000	5380	−3380	−84.5

Table 39.6 DTPA extractable heavy metal (ppm) after 39 years in Ranchi, Bhubaneshwar, and Ludhiana

Heavy metal	Control	NPK	NPK + Lime	NPK + FYM	Fallow
Ranchi					
Pb	0.15	0.20	0.45	0.16	0.20
Ni	0.12	0.21	0.40	0.15	0.13
Cd	0.10	0.14	0.25	0.19	0.11
Bhubaneshwar					
Pb	0.85	0.9	1.3	1.50	–
Ni	0.16	0.12	0.18	0.06	–
Cd	0.02	0.025	0.01	0.01	–
Ludhiana					
Cr	0.02	0.05	–	0.24	–
Ni	0.2	0.20	–	0.3	–
Cd	0.01	0.08	–	–	–

(Table 39.6). The di-ammonium phosphate (DAP) contains Pb in variable ranges due to the use of phosphate of rocks as base material. Increase in Pb is also noted on application of lime and FYM. Lime contains lots of impurity in the form of heavy metals. However, at Ludhiana Cr was recorded in plot received FYM. Since FYM is an input from animal dung which is fed on fodder probably grown on soil contaminated with Cr. But the content of heavy metals is far below the safe limits prescribed in the literature.

39.10 Biological Status of Soil

Data on microbial counts (Fig. 39.4) and microbial biomass carbon (Fig. 39.5) at different locations indicated that application of fertilizer in balanced manner improved the counts of various microbes', viz., bacteria, fungi, actinomycetes, etc.

Microbial biomass carbon (MBC) acts as substrate for soil organisms and larger amount of substrate helps in maintaining larger in population which in turn generate more nutrient to plant and produce the substance which help in binding the smaller

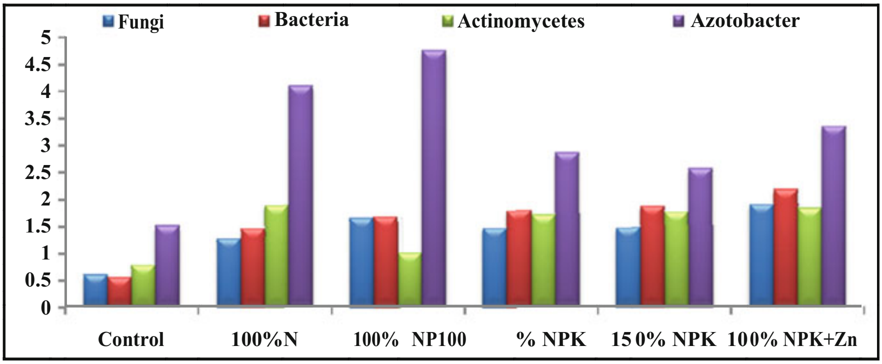

Fig. 39.4 Effect of nutrient management on microbial biomass carbon (mg kg^{-1}) in soil at Pantnagar center

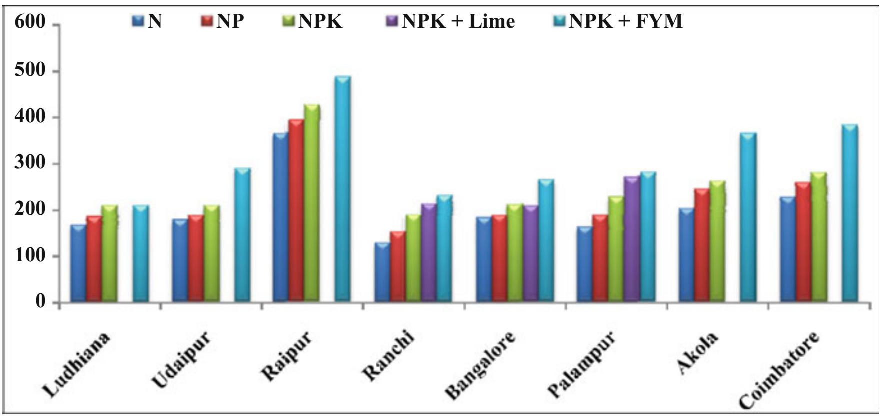

Fig. 39.5 Long-term effect of fertilizer and manure on microbial population in soil at different LTFE centers

aggregate to bigger aggregate. Data further indicated that imbalance use of nutrient (e.g., N) alone had negative effect on population of these organisms when compared with balanced treatment but superior to control. This indicates that soil biota also required nutrient for their multiplication and growth. Incorporation of biomass in larger quantity through root and stubble as a result of higher productivity in the plot receiving balanced nutrient application favored microbial proliferation. Hence to maintain good biological condition of soil application of nutrient is essential. From the data of last 46 years it is clear that application of fertilizer in balanced manner did not have any adverse effects on soil microbial population and activity, hence, LTFE ruled out that chemical fertilizer killed the soil microorganisms.

39.11 Soil Quality

To assess soil quality, indicators (soil properties) are usually linked to soil function (Doran et al. 1996; Karlen et al. 1996). A valid soil quality index (SQI) would help to interpret data from different soil measurements and show whether management and land use are having the desired results for productivity, environmental protection and health (Granatstein and Bezdicek 1992).

SQI is relative numerical figure which indicate the condition of soil at that point of time under a particular management and how it has affected by our management practice. More is the SQI better is the soil quality. By using this concept, soil indicators were identified through principal component analysis (PCA) and using their relative contribution in productivity. Analysis of data (Fig. 39.6a–c) revealed that in Alfisols; pH, microbial biomass carbon, N, Available K are important indicators, in Vertisols; soil physical indicators like infiltration rate, bulk density, soil carbon were found predominant indicators, whereas in Inceptisols in addition to SOC, available nutrients (N, P, Zn, etc.) appeared important soil indicators. Soil carbon is one of the common indicators in all soil. Data further suggested that balanced application of nutrient resulted increase in soil quality.

39.12 Carbon Sequestration

Increase in SOC stock from its reference value (initial) is referred as C sequestration and decline in SOC is referred as depletion of SOC. Data presented in Table 39.7 revealed that in some of the treatments there has been net increase in SOC stock, but in other treatments depletion in C stock was recorded. Carbon stock data in Mollisols of Pantnagar revealed that in all the treatments except 100% NPK + FYM decline in SOC stock was recorded which means in all the nutrient management practices there is net loss of SOC. This resulted decline in soil C from 1.48 to 0.61% during last the 40 years which clearly demonstrates that we shall have to add more C through organic sources FYM, residual biomass, green manure. In contrary to Pantnagar at other places, balanced application of nutrient, i.e. NPK or some time NP (where crop did not response to applied K) either maintain or increased SOC. Increase in amount

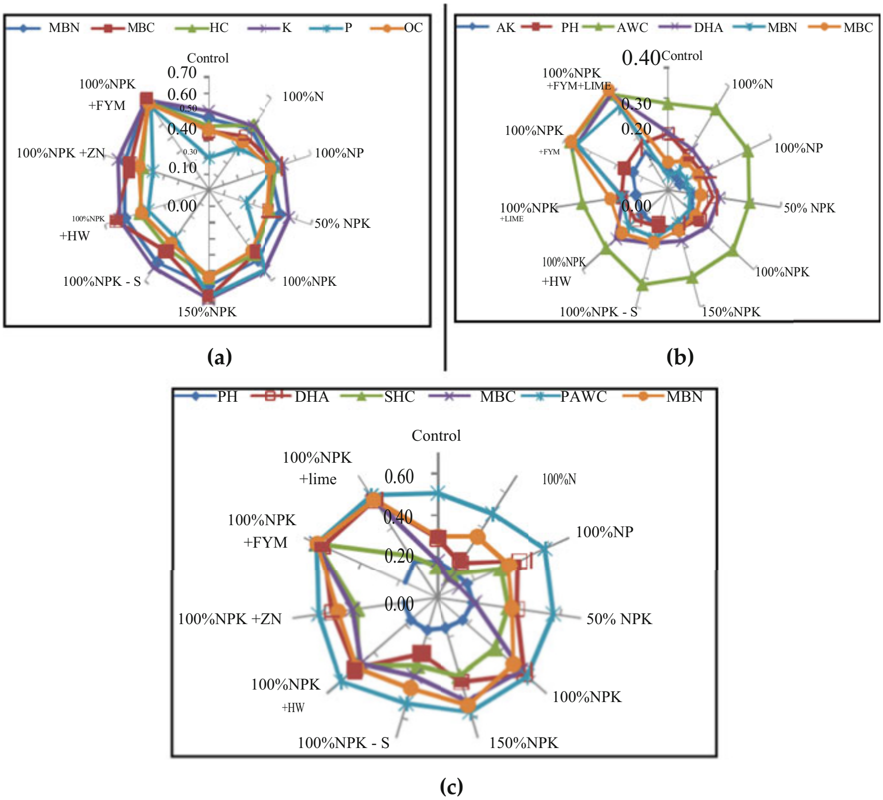

Fig. 39.6 Soil quality index under different nutrient management options. (**a**) Coimbatore. (**b**) Bangalore. (**c**) Palampur

of nutrient (NPK) from 50 to 150% resulted increase in C sequestration which is due to increase in total biomass or primary productivity of crops (Kundu et al. 2001, 2007). It is interesting to note at Ludhiana, decline in SOC was not recorded even in control plot. This is because these soils were at minimum level of C beyond this; there will not be any loss of C from soil what so ever practice you adopt. Thus, balanced application of nutrient not only sustained the crop productivity but also pumped atmospheric C to soil through crop residue and helped in mitigation of climate (Singh et al. 2019).

Table 39.7 Depletion/sequestration in soil carbon stock (0.20 m) under different nutrient management options

LTFE locations	Control (kg ha^{-1} $year^{-1}$)	100% N (kg ha^{-1} $year^{-1}$)	100% NP (kg ha^{-1} $year^{-1}$)	100% NPK (kg ha^{-1} $year^{-1}$)	150% NPK (kg ha^{-1} $year^{-1}$)	100% NPK + FYM (kg ha^{-1} $year^{-1}$)
Pantnagar (after 40 year)	−539.4	−432.7	−372.0	−432.2	−417.5	50.3
Barrackpore (after 40 year)	−51.9	−4.1	26.2	93.9	107.9	160.2
Raipur (after 20 year)	−173.1	−26.1	58.7	53.5	79.3	156.6
Akola (after 20 year)	−45.0	−5.0	45.0	125.0	175.0	245.0
Jabalpur (after 34 year)	58.8	123.5	135.3	214.7	241.2	311.8
Ranchi (after 40 year)	−10.0	−22.5	−40.0	15.0	40.0	90.0
Ludhiana (after 40 year)	5.0	85.0	105.0	117.5	117.5	167.5

Note: Initial C content (Mg ha^{-1}) in 20 cm depth at Pantnagar = 38.8, Barrackpore = 11.8, Raipur = 16.2, Akola = 17.1, Jabalpur = 17.6, Ranchi = 14.4, and Ludhiana = 9.8

39.13 Superimposition of Treatments

39.13.1 Reutilization of Accumulated Soil P

One of the important lessons learnt from LTFE was continuous application of P increased the P status of soil and absence of P in fertilizer resulted decline in P status of soil. So to verify the findings soil sample were collected from farmer's field in the district of Ludhiana, Jalandhar, and Nawanshahr district of Punjab and noted high to very high P content. To reutilize accumulated soil P and to avoid adverse effect on environment, a strategy was developed. The yield data (Table 39.8) revealed that as a

Table 39.8 Dynamic in soil Olsen's P with time and impact of P dose to half on crop productivity

	P status (mg kg^{-1} $year^{-1}$)		P rate (mg kg^{-1} $year^{-1}$)		Average yield (t ha^{-1})	
Treatment	1994	2006	Increase	Decrease	Maize	Wheat
100% NK +100% P	34.3	41.1	1.07		5.83	5.64
100% NK + 50% P	–	28.7	–	−0.46	5.72	5.59
CD ($P \leq 0.05$)	–	28.5	–	−0.46	0.20	0.15

Initial $P = 4$ mg kg^{-1}

result of reduction of P dose to half did not have adverse effect on crop productivity of either maize or wheat. At the same time similar strategy was implemented in farmer's field also and found the similar kind of yield trend and there was no reduction in crop productivity. To further strengthen our findings P status in soil was measured and noted that continuous use of 100% P in both crops resulted in increase in P status in soil at 1 ppm every year. Whereas reduction in P application to half resulted decline in soil P status to 0.46 ppm (Singh et al. 2016). On the basis of results it was decided to apply 100% P in *rabi* crop and *kharif* should be grown on residual P. The moisture availability and high temperature during *kharif* will take care of mobilization of residual P. Thus on adoption of strategy, one million tons of fertilizer P worth 50,976 is saved every year in intensively cultivated part of Northern India (Punjab, Haryana, and Western Uttar Pradesh).

39.13.2 FYM is Better Soil Amendment Than Lime for Management of Acid Soil

Another very important lesson learnt from LTFE was FYM works better than lime for sustaining productivity of acid Alfisols. To substantiate further, study was carried out at Ranchi and Bangalore were by superimposing lime and FYM in some of the treatments. In all the nutrient management option's incorporation of FYM proved to be better as far as crop productivity is concerned but the magnitude of different in yield went on increasing as we moved from NPK to NP and N alone (Tables 39.9 and 39.10). A similar kind of results was also obtained experiment conducted at research station as well as farmers' field (Singh and Wanjari 2010). Poor effect of

Table 39.9 Effect of superimposition of lime and FYM on productivity of soybean and wheat in Alfisols of Ranchi

Treatment	Soybean (*q* ha^{-1})	Wheat (*q* ha^{-1})	TSP (*q* ha^{-1})	Yield advantage over original (*q* ha^{-1})	Profit over original (` ha^{-1})
100% NPK[a]	15.2	27.9	47.46	–	–
100% NPK + Lime	22.6	31.7	60.79	13.32	14,390
100% NPK+ FYM (5t)	24.9	34.5	66.55	19.08	20,611
100% NP[b]	4.8	24.4	30.58	–	–
100% NP + Lime	8.1	31.7	42.13	11.55	12,471
100% NP + FYM (5t)	14.9	35.8	54.98	24.40	26,351

TSP total system productivity
[a]Average of last 35 years
[b]Average of last 4 years

Table 39.10 Effect of superimposition of lime and FYM on productivity of Finger millet and maize in Alfisols of Bangalore

Treatment	Finger millet (q ha^{-1})	Hybrid maize (q ha^{-1})	TSP (q ha^{-1})	Yield advantage over original (q ha^{-1})	Profit over original (` ha^{-1})
100% N	4.78	2.45	7.66	–	–
100% NPK + FYM	26.48	27.4	56.24	48.59	40,814
100% NPK + FYM + Lime	25.84	27.9	56.05	48.39	40,648

Table 39.11 Change in soil available K at different LTFE locations (kg ha^{-1} year^{-1})

Location (years)	Control (kg ha^{-1} year^{-1})	N (kg ha^{-1} year^{-1})	NP (kg ha^{-1} year^{-1})	NPK (kg ha^{-1} year^{-1})	150% NPK (kg ha^{-1} year^{-1})	NPK + FYM (kg ha^{-1} year^{-1})
Jabalpur (41)	−2.3	−2.1	−3.6	−2.7	*−1.9*	*−1.4*
Akola (26)	−1.7	−5.0	−4.2	+0.9	+2.6	+3.4
Junagarh (16)	−5.8	−6.8	−6.2	−4.5	−2.4	+1.0
Raipur (6)	−3.3	−6.8	−9.7	−5.0	−1.3	−3.1
Parbhani (6)	−3.5	NC(1)	NC	+4.3	+7.3	+9.1

lime under N treatment is due to short supply of P and K due to continuous absence of both nutrients in fertilizer schedule. Thus results confirmed that for sustaining the productivity of Alfisols incorporation of lime and organic manure is essential. But incorporation of FYM was found to be more effective than lime and could be for long-term sustainability.

39.13.3 Potassium Response in Vertisols

Potassium (K) is one of the essential nutrients required in large quantity by the crop plants. Available reports on soil K status indicated that Vertisols are rich in K status, but absence of K in fertilizer schedule or very little of K has resulted in inadequacy of K in several soils which threats to get potential yield of crop. Results generated over the years in the LTFE indicated that at five Vertisols or associated Vertisols centers which were considered rich in potassium (K), crops began to show response to K fertilizer application. Analysis of soil K status (Table 39.11) revealed that in absence of K in the fertilizer schedule resulted in a decline in K status from 2.1 to 9.7 kg ha^{-1} year^{-1} and addition of N and P accelerated the mining of K. On the other hand, the decline in available K status was arrested by the addition of K (NPK and NPK + farm

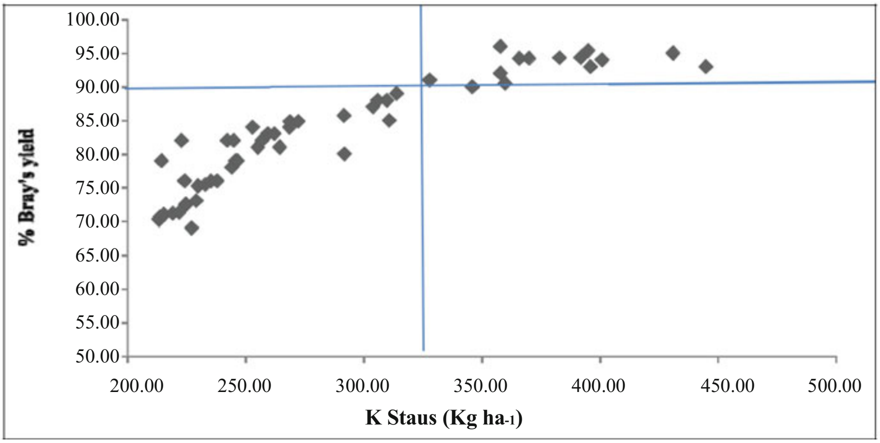

Fig. 39.7 Critical limit of potassium in Vertisols by using rice and wheat as test crops at different locations

yard manure; FYM) and noted to be positive (Singh and Wanjari 2014). The relationship between available K status and Bray's percent yield indicated ~335 kg K ha^{-1} as a threshold value for Vertisols rather than the current recommendation being used in India of 280 kg ha^{-1} (Fig. 39.7). This finding indicates that there is need to modify or raise the critical limit for K rating of Vertisols, otherwise a lack of K could pose a threat to sustainability.

39.14 Conclusion

From the results of four and half decade old long-term fertilizer experiments, concluded that balanced application of nutrient enhanced crop productivity, improved soil health/quality and overall sustainability of the system. Balanced and integrated use of nutrient improves nutrient use efficiency and increased the sustainability yield index (SYI) over the years which indicate better crop productivity. Results of LTFE across the locations demonstrated that proper management of nutrient increased SOC and microbial population in soil, thus, ruled out that use of chemical fertilizer deteriorate SOC and kills soil microorganism. After attaining the sufficiency P status in soil skipping of P in *kharif* crop would avoid unnecessary accumulation of P in soil without any loss in crop productivity and also minimize water pollution through Eutrophication. Continuous absence of K in fertilizer schedule or application in less quantity than removed by crop resulted in crop response in Vertisols due to poor release of K from non-exchangeable K and reduction of K in available pool. The critical limit of available K in Vertisols found to be ~335 kg K ha^{-1} against the current value of 280 kg K ha^{-1}. Studies proved that incorporation of FYM was found to be more effective than that of lime for sustaining the productivity of Alfisols. Thus from the study under long-term fertilizer experiment it is concluded that balanced and integrated use of nutrient not only sustained crop productivity and improved soil quality/health but also helped in mitigating climate by assimilating more atmospheric CO_2 through photosynthesis and pushing more carbon into soil through C sequestration.

39.15 Issue for Future Research

Ever increasing population pressure, man is forced to do activities which affect soil ecology and may adversely affect soil to perform its function like water retention and purification, organic waste decomposition and nutrient cycling, etc. So it is essential to take care of soil for future generation. AICRP–LTFE is good platform to address the issues which can be used for assessing degradation and functioning of soil. Thus there is need to undertake the work on following issues extensively:

- Work out the optimum nutrient management practices for carbon sequestration.
- Assessment on functional diversity of soil microorganisms and ecosystem services of soil.
- To study the impact of changing climate on crop productivity and soil health.

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Micronutrient Deficiency Stress in Soils of India: Tackling it to Alleviate Hidden Hunger

40

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Abstract

Micronutrients have a significant role towards achieving sustainable crop production. But, Indian soils are considerably poor in micronutrient fertility especially of zinc, iron, manganese, copper, boron and molybdenum as these have consistently been pulled out from the soil system due to repeated cultivation for a prolonged period without proper replenishment. The resultant stress in Indian soils related to micronutrient deficiencies has become a major limiting factor towards improved productivity and quality of crops grown in these soils. When deficiency reaches a severe level, plants start showing characteristic disease symptoms. However, under marginal deficiency, plants do not show any symptoms but results in lower yield and this situation is called 'hidden hunger'. The problem of hidden hunger (micronutrient malnutrition, mainly of zinc and iron) is also alarming among human population, affecting mainly the masses in developing countries who are mostly dependent on poor quality plant products (obtained from soils suffering in micronutrient deficiency stress) for their daily energy requirement. Hence, there is need to understand the severity of micronutrient deficiency stress existing in soils of India and adopt suitable management practices aimed at

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increasing the soil available micronutrient pool in order to address the hidden hunger situation both in plants and human beings.

Keywords

Micronutrient · Indian soil · Hidden hunger · Management

40.1 Introduction

Micronutrients, namely zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), boron (B), molybdenum (Mo), etc., are essential elements that play a crucial role in the growth and development processes of living beings, viz., plants, animals and human beings. Every micronutrient has a specific role to play in the living system and is hence considered to be essential. Maintenance of their adequate level in both plants and animals, including human beings, is indispensable for completion of their respective life cycles. When any of these nutrients is present in quantity below the optimum level, i.e. deficient, all the essential processes including the important enzymatic reactions which are dependent on that micronutrient are disrupted (Lordkaew et al. 2013). Since these nutrients generally enter the food chain from the soil, maintenance of an adequate level of micronutrients in the soil is very important. However, their deficiency in soil is increasing alarmingly across the globe; soils of India are not an exception to this. Continuous use of micronutrient-free high-analysis fertilizers, minimal use or complete neglect of organic manures under intensive cultivation practices and adoption of high yielding varieties (HYVs) of crops have led to the problem of excessive removal of micronutrients from the soil as compared to their replenishment into the soil, thus causing widespread deficiencies. Inadequate supply of micronutrients from soil leads to impairment of normal metabolic processes in plants and thus causes severe yield and quality losses of different crops. Micronutrient deficiencies in the soil are, therefore, considered as a serious form of stress affecting the yield potentiality. Apart from this, the poor nutritional quality of agricultural produce also affects the health status of animals and human beings and thus contributes to the global burden of diseases in them. This is particularly true in developing countries like India, where huge masses of people depend mainly on plant-based diets (obtained from plants grown on soils highly deficient in micronutrients) for their nutritional requirements.

Therefore, management of widespread micronutrient deficiency stress in soils of India is of utmost importance for increasing crop productivity, producing micronutrient-rich agricultural produce which may further help in maintaining and improving the health status of animals/human beings. However, since, there is only a narrow range between the deficiency and toxicity level of the micronutrients, management practices should be adopted very cautiously (with a proper assessment of micronutrient availability status in soils) across the diverse agro-climatic situations of the country.

40.2 Concept of Hidden Hunger

40.2.1 Hidden Hunger in Plants

Micronutrients are highly essential for crop growth, and hence, deprivation of any of them leads to impairment of normal biological and physiological processes in the plant system. There is a critical concentration level of each micronutrient in plants, below which normal functioning of plants is hampered. Severe micronutrient deficiency level in soil and plants can be well understood from the appearance of specific visible plant symptoms or abnormalities. But, in many cases, under marginal deficiency, plants often do not show any visible symptoms. Thus, it becomes complicated to detect the presence of particular micronutrient deficiencies in those cases. This situation is known as hidden hunger, which causes crops to yield less than their potential level. It can be found that, in this case, despite the application of a recommended dose of NPK fertilizers, the yield remains lower due to the hidden hunger of micronutrients and thus, farmers lose potential profit. In this situation, crops respond to the application of the particular micronutrient. This form of hidden hunger in crops can be tackled by getting soils and plants analysed in the laboratory in advance and accordingly following proper management practices based on such soil-plant analysis results.

40.2.2 Hidden Hunger in the Human Population

Micronutrients are essential for sustaining the health of animals and human beings. Among all micronutrients, zinc (Zn) and iron (Fe) have a significant bearing on human health. However, it has been reported that there is a rampant increase in micronutrient malnutrition among human beings. According to a report by the World Health Organization (WHO), almost two billion worldwide are affected by these micronutrient deficiencies, often termed as 'hidden hunger'. This particular term implies that the poor health, mental impairment, etc., caused by micronutrient malnutrition in human beings often remain invisible, i.e., hidden and not at all easy to detect. Zinc deficiency has been reported to affect one-third of the human population worldwide ranging from 4% to 73% in different countries (Hotz and Brown 2004). Deficiency of zinc causes poor growth and stunting, impaired brain function and development, mainly in new-borns. In contrast, iron deficiency in human beings is found to be resulting in poor mental and physical development. Besides, impairment in immunity caused by micronutrient deficiencies often leads to several infectious diseases such as diarrhoea and pneumonia (Graham 2008). According to a WHO report (WHO 2002), Zn deficiency is considered to be the fifth most important risk factor responsible for illness and death in the developing world. Even in India, the problem of micronutrient malnutrition (hidden hunger) is severe among human populations, particularly in children and women. It is reported that almost 25% of the population in India suffer from zinc deficiency, and more than 80% of pregnant women suffer from iron deficiency anaemia (IDA).

40.3 Factors Affecting the Availability of Micronutrients to Plants

Quantity of micronutrient available to plants cannot be judged only by the total content of that particular micronutrient present in the soil. This is because the plant availability of micronutrients is governed by the soil factors that influence micronutrient solubility in soil, and the plant factors which influence the extraction and uptake of micronutrients by plant roots from the soil solution.

40.3.1 Soil Related Factors

Micronutrients in the soil are present in different pools, viz., water-soluble (soil solution); exchangeable; adsorbed, complexed and chelated; associated with secondary minerals and as sparingly soluble oxides; and constituents of primary minerals (Viets 1962). Nutrients in these pools differ in their solubility. Since plant roots uptake nutrients from the soil solution, available pool in the soil is more important than the total micronutrient content in the soil in predicting their availability to plants.

Since various sorption-complexation processes govern the distribution of micronutrient in soil among its different pools with the soil components, changes in the soil environment have a substantial effect on the availability of micronutrients. Soil factors that affect the plant availability of micronutrients are soil type (soil texture, structure, clay mineralogy, etc.), soil pH, redox potential (Eh), soil temperature, quantity of soil organic matter, calcium carbonate content, presence of other nutrients, etc., apart from the total amount of micronutrients present in soil (Fageria et al. 2002; Alloway 2008). Out of all these factors, soil pH and soil organic matter content are of utmost importance in influencing phyto-availability of micronutrients in soil (Lindsay 1991).

40.3.1.1 Soil pH and Micronutrient Availability

Soil pH, an indicator of the degree of soil acidity or alkalinity, is considered to be the principal factor governing plant availability of micronutrients from the soil. In general, availability of micronutrients, except molybdenum, is higher in acidic soils ($pH < 7$) and decreases gradually with increase in soil pH. This is because an increase in soil pH indicates higher concentration of free hydroxide (OH^-) ions which tend to react with free cationic micronutrients, for example, Zn^{2+}, Mn^{2+}, etc., and cause precipitation of minerals, ultimately making them unavailable to plant roots. Lower availability of molybdenum in acidic soils is because of the presence of a high concentration of H^+, Fe^{3+} and Al^{3+} ions in these soils which react with anionic micronutrients like Mo, making it unavailable (Reddy et al. 1997). Highest availability of micronutrients generally occurs in soil pH ranging between 6.0 and 7.0, thus making this pH range favourable for crop growth.

40.3.1.2 Soil Organic Matter and Micronutrient Availability

Soil organic matter is the storehouse of nutrients, including macro- and micronutrients. Humus tends to hold the cationic micronutrients in soil and releases them into the soil solution gradually. This gradual release process helps in making the micronutrients available for plant uptake when required by the plants. The higher level of organic matter in soil enhances micronutrient availability by increasing the content of exchangeable and organic fractions, whereas reducing the oxide fractions of the particular micronutrient (Shuman 1988). Due to the favourable effect of organic matter in supplying micronutrients to crops, modern management practices involving intensive cultivation that depletes the soil organic matter has become the primary reason for the occurrence of widespread micronutrient deficiencies.

40.3.1.3 Factors Affecting the Availability of Individual Micronutrients

Zinc

Zinc availability in soil is affected by numerous soil factors, of which pH is an important one. Its availability decreases with an increase in soil pH, mainly due to the formation of insoluble zinc hydroxides. In calcareous soils, the presence of excess calcium carbonate results in chemisorption of zinc, making it unavailable to plants (Yasrebi et al. 1994; Alloway 2008). Waterlogged conditions, low soil temperatures, leaching acid soil conditions also cause a decrease in zinc availability. Organic matter content, on the other hand, enhances the availability of zinc by increasing the readily available exchangeable and organic fractions of zinc and reducing the quantity of zinc in oxide fractions (Li et al. 2007; Alloway 2008).

Iron

Iron is the fourth most abundant element of the earth's crust, constituting about 3–5% of soil. But, most of it remains in plant unavailable form. This is due to the interactions of iron with soil components, which lowers the availability. The solubility of iron-bearing minerals and also, the release of iron from such minerals is controlled by the dissolution–precipitation equilibrium (Lindsay 1988). Soil pH plays a significant role in maintaining this equilibrium. Since iron is present in two forms in the soils, viz. Fe^{2+} and Fe^{3+}, which differs in their solubility and availability to plants, any soil condition which alters the ionic forms, also influences the plant availability of iron. Generally, the availability of iron decreases with a gradual increase in soil pH (Khabaz-Saberi and Rengel 2010). Lower soil organic matter level and increased calcium carbonate content (in calcareous soil) can also make iron unavailable for plant uptake. Sometimes, the presence of other nutrients, viz., Cu, Zn, Mn, phosphate ions, etc., in excess amounts also renders non-availability of iron to plants.

Copper

The complexation process mainly governs chemistry of copper in the soil (Jones and Jarvis 1981; Behel et al. 1983; Temminghoff et al. 1997; Oorts 2013). Since it is adsorbed explicitly to different soil components, viz., soil organic matter, carbonates, clay minerals, hydrous oxides of Al, Fe and Mn (McKenzie 1980; Reed and Martens 1996), excess amount of these components results in making soil copper less available to plants. Adsorption of copper is a pH-dependent process, and thus soil pH also plays a significant role in influencing plant available copper in the soil. Generally, with an increase in soil pH, the availability of this nutrient decreases.

Manganese

Its redox state mainly governs availability of manganese from soil to plants, viz., presence of soluble Mn^{2+} and insoluble Mn oxides formed by oxidized species Mn (III) and Mn (IV) (Stumm and Morgan 1996; Hundal et al. 2019). Therefore, the quantity of plant available Mn in soil depends on soil pH, organic matter content, moisture and soil aeration status (Gotoh and Patrick 1972; Sparrow and Uren 2014; Hundal et al. 2019). Soil temperature also plays an essential role in manganese availability by influencing the activity of microorganisms involved in Mn-oxidation and reduction process (Sparrow and Uren 2014).

Boron

Availability of boron is governed by its sorption and desorption behaviour in soil. It is affected by a variety of soil factors including soil solution pH, soil texture, soil moisture, temperature, oxide content, carbonate content, organic matter content and clay mineralogy (Goldberg 1997; Goldberg and Su 2007; Niaz et al. 2007). Boron availability decreases with an increase in soil pH, especially in calcareous soils. Therefore, excessive application of lime in acid soils often renders the nutrient unavailable for plant uptake from soil (Scott et al. 1975). Coarse-textured soils have a tendency to leach out boron and thus found to contain less plant available boron than fine-textured soils (Raza et al. 2002). Lack of soil moisture (drought condition) reduces plant availability of boron because of less mobility of boron from soil to roots by mass flow and diffusion (Scott et al. 1975; Chiu and Chang 1985; Chang 1993; Barber 1995).

Molybdenum

The solubility of molybdenum in the soil is governed by several processes, viz., adsorption-desorption, precipitation-dissolution, ion complexation, etc. Since these processes are pH-dependent, availability of molybdenum from soil to plants is strongly influenced by soil pH (Lindsay 1972; Gupta and Lipsett 1981). Molybdenum absorption in the soil increases as pH decreases and is reported to reach the maximum absorption level at around pH 4. Presence of sesquioxides (Fe and Al oxides), organic matter in soil also governs the availability of Mo (Haque 1987). Its adsorption is positively correlated with sesquioxides, whereas negatively correlated with soil organic matter content. Deficiency of molybdenum can also arise because of excessive quantity of other nutrient elements, viz., sulphur, copper, etc., present in soil (Haque 1987).

40.3.2 Plant Factors

Soil physical and chemical properties play a significant role in influencing the plant available pool of micronutrients in the soil. However, uptake of these micronutrients by plants from soil solution is also governed by several plant factors. Thus, it can be seen that even under similar soil conditions, not all crops are equally sensitive to deficiency of a particular micronutrient. These differences are generally due to differential micronutrient requirement of crops for their survival and growth. Monocotyledonous (Gramineae family) plants and dicotyledonous plants often have different micronutrient requirements, for example, in case of boron, requirements by dicots (20–70 mg B kg^{-1}) are found to be 4–7 times higher than monocots (5–10 mg B kg^{-1}) (Marschner 1995). This is attributed to the differences in cell wall composition and the levels of pectin compounds present in them (Hu et al. 1996). Even cultivars of the same crop behave differently under the same soil nutrient availability condition. This further implies that the critical concentration of a particular micronutrient also varies among crops and their cultivars. Hence, it has been found that different crop species along with their cultivars show various degrees of susceptibility to micronutrient deficiencies; for example, durum wheat genotypes were found to be more sensitive to manganese deficiency than Aestivum wheat genotypes (Bansal and Nayyar 2000).

40.4 The Extent of Micronutrient Deficiency Stress in Soils of India

Plant available micronutrients in the soil are categorized into deficient and sufficient levels based on certain critical limits for each nutrient. For any particular micronutrient, levels in the soil below the required limit are categorized as deficient, and crop response to external micronutrient application is generally significant in this range. However, since the plant availability of micronutrients in the soil is influenced by numerous soil and plant factors, as discussed earlier, the critical limit also varies under different soil conditions in other cropping systems. Assessment of soil micronutrient status in India, based on all these different critical limits followed in a diverse range of agro-ecological situations in the country revealed widespread existence of soil micronutrient deficiencies. However, the nature and extent of it vary under different conditions with different soil, and crop management practices followed. Analysis of over 2 lakh geo-referenced soil samples across several districts of India by ICAR-All India Coordinated Research Project of Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants [AICRP-MSPE] revealed that majority (36.5%) of the soils are deficient in zinc followed by iron (12.8%), manganese (7.1%) and copper (4.2%) (Shukla and Behera 2017) (Table 40.1). The deficiency of Zn has been found to decrease in period of two decades when compared to the data by Singh (1998) (Table 40.1).

It has been observed that these micronutrient deficiencies in the soil are commonly induced under the following conditions: (1) soils which are inherently low in

Table 40.1 Micronutrient deficiency status in soils of India over two decades of India

Percentage of soil deficient							
Singh (1998)				Shukla and Behera (2017)			
Fe	Mn	Zn	Cu	Fe	Mn	Zn	Cu
11.2	5.1	48.6	7.0	12.8	7.1	36.5	4.2

micronutrients, such as those derived from parent materials low in their content, (2) soils of extreme alkaline nature and calcareous soils, (3) acid soils which are subjected to heavy leaching losses of nutrients, (4) light-textured sandy and gravelly soils, (5) soils low in organic matter content, (6) soils under moisture stress and extreme temperature conditions. All these soils suffer from stress due to deficiency of micronutrients and thus pose serious threats to crop production. However, the order of deficient micronutrients along with their extent may vary in different states. For example, a study conducted across several agro-climatic zones of Madhya Pradesh revealed deficiencies of Zn, Fe, Mn and Cu to be around 67%, 10.2%, 1.80% and 0.57%, respectively (Shukla et al. 2016). The extent of individual micronutrient deficiency in soils of India as obtained from study reports is detailed in Fig. 40.1.

40.4.1 Zinc Deficiency in Soils

Plant available zinc in soils (widely assessed as DTPA-extractable zinc) of India under various agro-climatic situations ranges from 0.01 to 52.93 mg kg^{-1} soil (Shukla et al. 2014). These zinc levels in soil have been grouped into sufficient and deficient ones based on critical limits for zinc in soil under different agro-ecological situations. Deficiency of zinc in soils of India is the most predominant one among all micronutrients, as revealed by study reports showing deficiency in 36.5% of Indian soils. However, the extent of deficiency varied among different states. Soils of Rajasthan showed higher zinc deficiency (75.3%) followed by Madhya Pradesh, Tamil Nadu, Maharashtra, Bihar, Uttar Pradesh showing 66.9%, 65.5%, 54.0%, 44.0%, 33.1% deficiency, respectively. Deficiency of zinc in soils of Uttarakhand was the lowest with 9.6% deficiency (Shukla et al. 2014). Even within the states, variation in soil type (pH, soil texture, organic matter content, etc.) leads to a wide variation in the deficiency status. A severe form of zinc deficiency prevails in intensively cultivated areas having soils with coarser soil texture, higher pH (sodic soils having pH > 8.5), higher calcium carbonate content (calcareous soils) and also soils with lower organic carbon content. Among the soil types, medium black soils are more deficient in soil zinc.

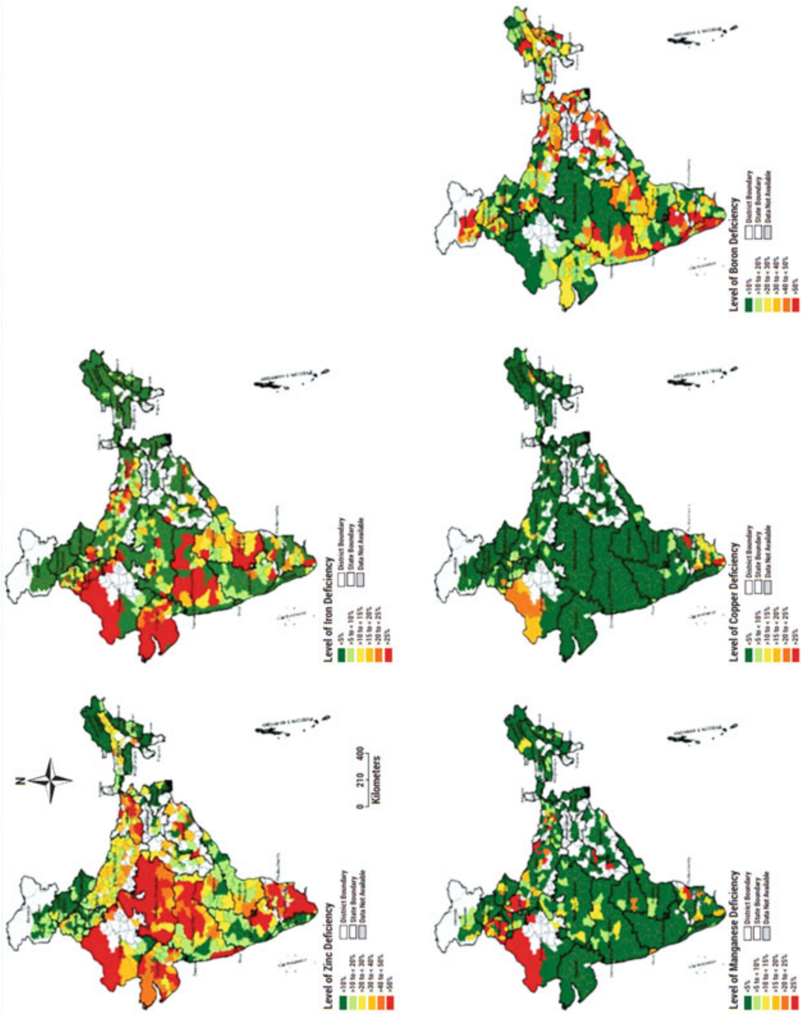

Fig. 40.1 Maps showing micronutrient deficiency status in different districts of india (Source: Shukla et al. 2018)

40.4.2 Boron Deficiency in Soils

Plant available boron content in soils (as assessed by hot water-soluble boron) is found to range from 0.01 to 237.50 mg kg^{-1} soil with an average of 1.24 mg kg^{-1} soil. Report findings show 23.2% of Indian soils to be deficient in boron, making boron deficiency as a primary form of micronutrient deficiency in soils of India, next to zinc deficiency (Shukla and Behera 2012). Leaching of boron in soils is of grave concern and is the primary reason behind the occurrence of its deficiency in sandy loam soils (Takkar 1996; Shukla and Behera 2012). Highly calcareous soils (often found in Bihar and Gujarat) and also acid soils (especially in north-eastern states of India, in eastern states of India including West Bengal, Orissa, Jharkhand) are prone to boron deficiency. Heavy liming of acid soils also causes boron to be deficient for plant availability (Takkar 1996). Grey-brown soils (46.3%), submontane soils (33.7%) and calcareous alluvial soils of India are found to be in general higher in boron deficiency (Shukla and Behera 2012).

40.4.3 Iron Deficiency in Soils

Plant available iron in soils (assessed as DTPA-extractable iron) varies from as low as 0.01 mg kg^{-1} to as high as 1461.70 mg kg^{-1} soil. Though soils are rich in total iron content, its availability to plants being influenced by many factors (as discussed earlier), is hindered under certain soil conditions. Alkaline soils having pH > 7.5 and calcareous soils are more prone to the occurrence of iron deficiency (Morris et al. 1990; Mengel 1994; Chen et al. 2016). Severe drought or moisture stress condition also affects the plant availability of iron from the soil. Because of these reasons, deficiency of iron in soils of India is more acute in states lying in its western parts, mainly Rajasthan, Gujarat and also in Maharashtra. There are also reports which show that iron deficiency in soils of India was earlier in 11.0% soils (during 1967–1897) and increased to 12.8% (during 2011–17) with Telangana, Karnataka, Bihar, Uttar Pradesh being the emerging states in the occurrence of deficiency (Shukla et al. 2014). The problem of iron deficiency is mainly in grey-brown soils and old alluvial soils among the different soil types existing in India.

40.4.4 Manganese Deficiency in Soils

Manganese availability (assessed as DTPA-extractable manganese) in soils of different parts of India varies from 0.01 to 444.90 mg kg^{-1} soil with an average of 21.78 mg kg^{-1} soil (Shukla et al. 2014). Its deficiency in soils is much lower than the deficiencies of zinc, boron and iron in soils of India. Iron deficiency is mainly observed in some pockets especially under rice–wheat cropping systems of Punjab and Haryana having coarse-textured highly permeable soils (sandy or loamy sand). These are the soils with low total manganese content, and as a result, plant availability is also automatically low. Organic-rich soils, soils having pH above 6, calcareous soils or even heavily-limed acid soils are the ones which are prone to be deficient in manganese (Sparrow and Uren 2014; Hundal et al. 2019).

40.4.5 Copper Deficiency in Soils

Plant available copper in soils (assessed as DTPA-extractable copper) of India ranges from 0.02 to 378.70 mg kg^{-1} soil. Copper deficiency is not a significant problem in Indian soils as a whole since less than 5 percent of soils shows the deficiency of the nutrient. But it is a cause of concern in some parts of the country, particularly in states like Tamil Nadu (13.0% soils deficient), Uttar Pradesh (6.3% soils deficient) and also in some pockets of Punjab and Haryana where intensive cultivation practices are followed (Shukla et al. 2014). Copper deficiency is mainly a problem in sandy soils, calcareous soils and soils high in organic matter content (Mengel et al. 2001; Rodriguez-Rubio et al. 2003). Old alluvial soils and laterite soils of India are more prone to the occurrence of copper deficiency.

40.4.6 Molybdenum Deficiency in Soils

The occurrence of molybdenum deficiency is sporadic in soils of India. Though a majority of Indian soils are sufficient in molybdenum content, its deficiency can be observed in specific localized patches where acidic soils and highly leached sandy soils prevail. Thus, some parts of states like Maharashtra, Orissa, Kerala, West Bengal, Himachal Pradesh have been reported to be moderate in molybdenum deficiency.

40.4.7 Multimicronutrient Deficiencies in Soil

Simultaneous occurrence of deficiencies of two or more micronutrients is emerging as a matter of crucial concern in soils of India (Patel and Singh 2010), apart from the occurrence of individual micronutrient deficiency. Excessive nutrient mining in areas where intensive cultivation practices are followed results in their deficiencies. From the last two decades, multimicronutrient deficiencies for Zn + Fe (5.85%), Fe + B (3.0%) and Zn + B (9.8%) have been noticed (Table 40.2).

Among the micronutrient combinations, the deficiency of Zn + B was much higher in states like Karnataka (23.4%), Bihar (20.3%), Tamil Nadu (13.3%) and Odisha (14.0%). Deficiency of Zn + Fe was prevalent in the area of Rajasthan (23.3%), Gujarat (11.7%) and Maharashtra (10.1%). Another combination of Fe + B deficiency was highest in Maharashtra (9.8%) (Singh 2006; Shukla and Tiwari 2016; Yadav et al. 2017).

Table 40.2 Deficiency status of micronutrients in soils of different states of India

State	Two micronutrients (%)		
	Zn + B	Zn + Fe	Fe + B
Andhra Pradesh	3.1	6.9	2.1
Assam	7.5	0.0	0.0
Bihar	20.3	5.1	8.0
Chhattisgarh	–	3.1	–
Goa	–	2.2	–
Gujarat	7.3	11.7	4.4
Haryana	0.7	6.5	1.3
Himachal Pradesh	5.1	0.1	0.3
Jammu and Kashmir	–	0.0	–
Jharkhand	10.1	0.0	0.0
Karnataka	23.4	3.9	1.9
Kerala	4.9	0.9	0.4
Madhya Pradesh	0.9	5.8	0.2
Maharashtra	7.9	10.1	9.8
Manipur	3.1	0.0	0.0
Odisha	14.0	3.8	3.4
Punjab	4.2	3.7	2.2
Rajasthan	3.3	23.3	0.4
Tamil Nadu	13.3	8.2	2.0
Telangana	8.9	4.7	4.1
Uttar Pradesh	8.0	4.7	1.4
Uttarakhand	0.9	0.2	0.0
West Bengal	4.9	0.0	0.0
All India	**9.8**	**5.8**	**3.0**

40.5 Strategies to Tackle Micronutrients Deficiencies in Soil

Management of micronutrient scarcity varies with crops, soil types, deficiency level, and time, dose, method and frequency of application. Thus, numerous aspects need to be considered while planning replenishment of micronutrients either removed by the crop and/or depleted from soil. There is a certain need to maintain effective balance between demand set by the plants and supply of these nutrients (which is both crop- and soil-specific) from the soil (Shukla et al. 2016; Dadhich and Meena 2014) (Fig. 40.2).

40.5.1 Fertilizer Management

Micronutrient deficiencies in soils can be prevented/corrected by external application of different fertilizer sources available in the market. Apart from the significant products, viz., straight, chelated form of micronutrient carriers, several technological

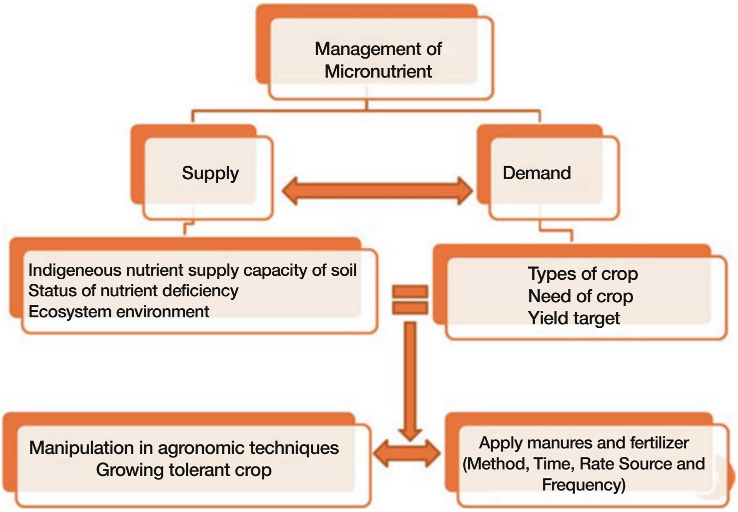

Fig. 40.2 Steps in micronutrient management in soil–plant system. (Modified from Shukla et al. 2016)

interventions are also being used to formulate fertilizers that may help in managing micronutrient deficiencies in soil under a diverse range of agro-climatic situations; nanotechnology is one prominent option among them (Tarafdar et al. 2014). However, the required rate of application of fertilizers and the response obtained from them vary with agro-climatic factors, viz., type of soil and crops, the severity of the deficiency, source of fertilizer, method of application, etc. Site-specific micronutrient applications are highly advised, and this can be possible with modern advance tools like GPS, GIS, etc., that facilitate in developing accurate and precise maps of micronutrients in the soil. Micronutrient fertilization to soils and crops, apart from enhancing soil fertility and crop productivity, also helps in producing micronutrient-rich grains/seeds. Such quality plant products can ultimately help in reducing the hidden hunger, i.e. micronutrient malnutrition when animals or human beings consume the products.

40.5.1.1 Zinc

There are several sources of zinc fertilizers which can be used for correcting its deficiency. Takkar et al. (1989) reported a significant increase in wheat grain yield over control in Vertisols of Jabalpur and Anand and Inceptisols of Hisar in India due to application of Zn carriers like zinc sulphate, zinc oxide, zinc phosphate, zinc chloride, zincated superphosphate, zinc silicate and zinc frits to Zn-deficient soils. However, out of all these, zinc sulphate is the most commonly used and efficient one (Mortvedt and Gilkes, 1993). The efficiency of synthetic Zn-EDTA was comparable with zinc sulphate. However, the high cost of Zn-EDTA makes this fertilizer most uneconomical and less effective for common use. Farmers can easily accept this fertilizer source because it is economically cheaper and also commonly available apart from its highly soluble nature and good physical properties. Zinc sulphate, both in its monohydrated form ($ZnSO_4.H_2O$) and hepta hydrated form ($ZnSO_4.7H_2O$) are equally efficient. It can be applied either through soil or through foliar application. In India, soil application of Zn in the range of 2.5–22 kg Zn ha^{-1} is recommended for different crops/cropping systems and soil types (Takkar et al. 1989). Higher application is preferred for sensitive crops and acutely deficient soils. Amount of zinc required for alleviating zinc deficiency varied with the severity of the deficiency, location/soil types, nature of crops and cultivars. Fertilizer Zn requirement of crops was found to be double in coarse-textured loamy sand soil than in fine-textured loam or clayey soil for wheat and rice. In the case of the cereals, application of 5.0 kg Zn/ha was sufficient to meet the Zn requirement of 2-3 crop cycles as Zn leaves marked residual effect for succeeding crops. But, in the case of soil application, fertilizer use efficiency of Zn applied seldom exceeds 5% (Mortvedt 1994). This is mainly due to the uneven distribution of zinc while applying a small quantity of it (required for plant growth) in soil and reaction of applied zinc with various soil components to form unavailable products and thus low mobility in soil. So, foliar spray of zinc sulphate @ 0.5% to crops works as wonders when supplemented with soil application. However, in highly zinc-deficient soils, foliar spray can be a supplement, but not a substitute to soil zinc fertilization. Also, in some cases, seed coating and root dipping are successful in correcting zinc deficiency to some extent, but with zinc oxide and zinc phosphate as sources of zinc. Timing of zinc fertilization depends upon the severity of its deficiency in the soil, seed zinc content, and also the mode of application. In case of soil zinc fertilization, basal application through broadcast or band placement below the seed proved superior. Foliar application at tillering and flowering stages of wheat supplemented with the basal application has been found to be highly efficient in zinc-deficient soils. Recognizing the importance of zinc in agriculture, macronutrient fertilizers blended with zinc, viz., zincated urea, zincated superphosphate have come up as a possible option for balanced fertilization. Still, they alone cannot be effective in correcting zinc deficiency in soils highly deficient in these nutrients. Range of response to all these modes of zinc fertilization through different sources is however location- (soil, climate type) and crop-specific and thus varies across other states of India taking into account the diverse nature of agro-climatic situations available in the country.

40.5.1.2 Boron

Different sources of boron can be used to prevent/correct B deficiency in crops. [borax ($Na_2B_4O_7.10H_2O$ with 11% B), solubor—$Na_2B_8O_{13}.4H_2O$ (20% B), sodium borate ($Na_2B_4O_7.5H_2O$ with 20% B), sodium tetraborate ($Na_2B_4O_2.5H_2O$ with 14% B), boric acid (H_3BO_3 with 17% B), Colemanite ($Ca_2B_6O_{11}.5H_2O$ with 10% B), B frits containing 2-6% B and boronated superphosphate. Among all these sources, borax is the most commonly used boron fertilizer. However, B frits are effective for long-duration crops, including fruit trees owing to their low solubility and thus slow boron releasing nature. Because of the extremely narrow range between sufficiency and toxicity levels of boron, extreme care should be taken in deciding the quantity of boron fertilizer needed and applying it, since excess dose can affect crop growth

(Gupta 1980; Marschner 1995; Zia et al. 2006). Depending on soil type, crop requirement and method of application of boron fertilizer, its dose generally varies from 0.25 to 3.0 kg B ha^{-1} (Dwivedi et al. 1990; Mortvedt and Woodruff 1993). Soil application of boron @ 0.5 to 2.5 kg B ha^{-1} gave a crop response of 108–684 kg grain/kg of B or 10–44% over NPK in boron-deficient soils present in different states of eastern and north-eastern India, viz., West Bengal, Assam, Bihar, Orissa, etc. In calcareous soils of Bihar, the required application rate for optimum yield of different crops ranges between 1.0 and 2.5 kg B ha^{-1} (Sakal et al. 1988; Sinha et al. 1991). Higher rate of application is required when boron fertilizer is broadcasted rather than foliar application. Also, under dry soil conditions which restrict the uptake of boron by plant roots, the foliar application is more effective (Mortvedt and Woodruff 1993). Since boron is critical for reproductive development of plants, boron foliar fertilization at the onset of reproductive phase is efficient in reducing severe yield losses (Ahmad et al. 2009). In case of hidden boron deficiency, foliar sprays of 0.2% boric acid or borax at pre-flowering stage have been found to enhance crop yield.

40.5.1.3 Iron

Iron fertilization through soil application is less efficient and economical than foliar sprays. Foliar sprays of 1–2% unneutralized ferrous sulphate solution three to four times efficiently correct the iron chlorosis. Iron chelates are more efficient as fertilizer materials than inorganic sources. Still, due to its high cost, it is less preferable to farmers for use in field crops, except in some high value-cash crops. In general, crop responses to soil and foliar application of Fe ranges from 0.45 to 0.89 t/ha for cereals, 0.3 to 0.68 t/ha for millet, 0.34 to 0.58 t/ha for pulses, 0.16 to 0.55 t/ha for oilseeds, 0.20 to 1.53 t/ha for vegetables and 0.39 to 9.68 t/ha for cash and other crops (Shukla and Behera 2012).

40.5.1.4 Manganese

Manganese fertilization can be done through the soil and foliar application, though foliar fertilization is more efficient; for example, in case of wheat grown in sandy soils, three to four foliar spray of 0.5–1.0% $MnSO_4$ solution proved to be better than basal application. Mn application can cause marked response when applied to crops grown in Mn-deficient soils. The responses have been found to range from trace to 1.78 t/ha for rice, trace to 3.78 t/ha for wheat, 0.03 to 1.02 t/ha for soybean, 0.40 to 0.70 t/ha for sunflower, 3.63 to 4.30 t/ha for onion and 0.30 to 0.80 t/ha for tomato (Shukla and Behera 2012).

40.5.1.5 Copper

Copper sulphate is a widely used fertilizer material for soil application as well as a foliar spray to ameliorate Cu deficiency. Crop responses to Cu application ranged from trace to 1.78 t/ha of cereals, 0.20 to 0.30 t/ha of millets, trace to 0.80 t/ha of oilseeds, 4.43 to 6.18 t/ha of onion and 0.30 to 0.50 t/ha of sugarcane (Shukla and Behera 2012).

40.5.1.6 Molybdenum

Ammonium molybdate and sodium molybdate are the most common sources of molybdenum fertilizer which can be used to prevent or correct its deficiency in soils and crops. Molybdenum fertilization can be made through soil application, foliar application or seed treatment. Seed treatment is the most effective one, followed by soil and foliar application. This is because seed treatment allows the uniform application of the nutrient, unlike soil application, where the application of a small amount of fertilizer uniformly is difficult. Though molybdenum is essentially required in significantly less quantity by crops, its fertilizer requirement rate varies depending on soil and crop type, fertilizer source, method of application, etc. Molybdenum fertilization @ 0.4–0.5 kg Mo ha^{-1} is sufficient to meet the crop requirement in Mo deficient red acid soils.

40.5.2 Management Options Other than Fertilizers

Apart from inorganic fertilization, several other soil management practices help to prevent micronutrient deficiencies in soil and plants. Organic manuring helps in maintaining a steady supply of micronutrients in the soil. Regular application of farmyard manure (FYM) @ 10–15 t ha^{-1} is beneficial. However, in situations where the application of organic manure annually is not possible, one can apply on alternate year to prevent emerging deficiencies of micronutrients in the soil. In cases where an adequate quantity of organic manures is not available, a small amount of organics can be applied to soil supplemented with half the recommended dose of fertilizers for sustaining the micronutrient supply from soil to plants. It has been found that the beneficial effect of the application of FYM or other organics in combination with zinc fertilizer is higher as compared to the application of zinc fertilizer alone. This is because the residual effect of nutrients applied through organic wastes is much higher than that of nutrients used through inorganic fertilizer sources. Zn-enrichment with organics has been found to possibly reduce rate of Zn application to wheat by one half of the recommended dose of 5 kg Zn ha^{-1}. Zn-enriched poultry manure and biogas slurry at Zn 2.5 kg ha^{-1} improved the average wheat grain yield by about 32% and 17%, respectively, over Zn application as zinc sulphate equivalent to 2.5 kg Zn ha^{-1}(Rathod et al. 2012).

Green manuring is also found helpful in mobilizing the native pool of micronutrients and improving micronutrient availability from soil to plants. Still, it is not a practical option in areas where intensive cultivation is practised. Incorporation of Sesbania green manure on a regular interval before paddy transplanting has been found to significantly improve paddy yield over that in the non-green manured plots which was attributed mainly to the enhanced supply of micronutrients in soil, particularly Fe and Mn, accompanied with increased soil organic carbon content (Nayyar and Chhibba 2000). Green manure application combined with a foliar spray of ferrous sulphate has been found to be more effective in enhancing crop yield than the sole application of either green manure or ferrous sulphate foliar spray.

Managing soil moisture levels through management practices is also sometimes helpful (Gotoh and Patrick 1974; Mandal et al. 1992). Since, iron availability in soil is highly influenced by its redox state, with a higher degree of oxidation of the nutrient element rendering it unavailable to plant, iron deficiency can be effectively controlled in a paddy field by raising them under puddled nursery beds supplemented with application of organics such as FYM, compost, etc. These help in maintaining soil iron in its reduced state which is more mobile and available for plant uptake. It has been found that the use efficiency of zinc fertilizers applied to rice under red and lateritic soils increases by preflooding, since it lowers the Zn-fixing capacity of such soils (Mandal et al. 1992). Under submerged conditions, higher valent forms of Mn like MnO_2, Mn_2O_3 and Mn_3O_4 get reduced to Mn^{2+} form which is more available to plants. Such reduction of Mn oxides has been found to be even more when flooding condition was combined with green manuring (Dhaliwal et al. 2019).

Conservation agriculture based cropping systems have been found to significantly influence the availability of micronutrient cations (Fe, Mn, Zn) in surface soil (Jat et al. 2018) which might be attributed to their greater addition through crop residue incorporation (Ghosh et al. 2010) and simultaneous accumulation in soil.

Besides agronomic management practices, microbial and physiological interventions can also help in mobilizing micronutrients in soil and thus prevent the occurrence of their deficiency related stress. Plant growth promoting rhizobacteria (PGPR) have been observed to increase the solubility of Fe in soil and thereby increase its availability to plants, mainly due to its siderophore producing ability (Zabihi et al. 2011). Arbuscular mycorrhizal (AM) fungi may also be helpful in increasing the uptake of different micronutrients including Zn by the host plant (Johnson 2010). However, in case of microbiological interventions, it is very important to choose the right microbial species, which can itself survive under such nutrient deficiency related stress.

40.6 Conclusion

Plants often experience a combination of various stress including drought, high irradiance, UV radiation, chilling, flooding and salinity. These stress factors are further aggravated by imbalanced nutrition of plants. Micronutrients, which form a vital component of balanced nutrition, are increasingly lacking in the soil system which ultimately hampers plant growth and productivity. Though the extent and effect of micronutrient stress in soil as well as in plants can be well understood under severe cases from the appearance of specific visible plant symptoms or abnormality; but, in many cases, under marginal deficiency, plants suffer from hidden hunger which causes lower crop yield and quality. Micronutrient stress in soils resulting in low quality plant produce may also lead to micronutrient malnutrition (often termed as hidden hunger) in the human population, severely affecting their health and contributing significantly to the global burden of diseases in them. Therefore, proper knowledge of the extent and severity of micronutrient stress in soils and also adoption of suitable measures to tackle such stress in soil itself through proper management options are of utmost importance for increasing crop productivity, producing micronutrient-rich agricultural produce which may further help in maintaining and improving the health status of animals/human beings. Measures to tackle these micronutrients' deficiency related stress in soils can be broadly of two types, one is through direct supply of particular micronutrient deficient in the soil and the other is through management of the soil environment in a manner which helps to maintain soil micronutrients in mobile pool, thus preventing the occurrence of micronutrient deficiencies. Since, efficiency of these approaches/measures vary across the diverse agro-climatic situations of the country, viz., type of soil and crops, the severity of the deficiency, etc., site-specific micronutrient management options should be adopted.

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Pesticide Pollution in Soils and Sediment in India: Status, Impact and Countermeasures

41

Ajoy Saha, Rakesh Kumar Ghosh, and Debarati Bhaduri

Abstract

Indiscriminate use of pesticides will lead to their accumulation in soil and may impart an adverse impact on human and environmental health. Due to the intensification of agriculture, usage of pesticide is inevitable in India; however, in the absence of a strong legal framework and lack of awareness of the farmers, inappropriate use of pesticides contributed to the pollution of soil and sediments and induced health problems for human and aquatic lives. Some of the pesticide molecules and its derivatives persist in the soil for a longer period which disturbs soil ecological balance and sustainability. Moreover, traces of pesticides may cause threat to the aquatic endangered species. This is a serious concern for both soil and aquatic environments. Reviewing various literature it was found that the level of contamination in soil and sediment does not reflect the present pesticide usage scenario of India and further highlighted the widespread use of banned pesticides. Under these circumstances, this chapter describes the occurrence, distribution and source of pesticides in the Indian scenario based on the numerous studies conducted over the past decades in both soil and sediment environments. The impact of these pesticides on soil ecology is also discussed along with the mention of novel and effective bioremediation methods invented by team of researchers to overcome the problem of pesticide residues.

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Keywords

Soil pollution · Sediment contamination · Biomagnification · Aquatic pollution · Pesticide residues analysis · Abatement of pesticide pollution · Soil ecological disturbances · Banned pesticides

Abbreviations

OCP	Organochlorine pesticides
OP	Organophosphorus
SP	Synthetic pyrethroids
HCH	Hexachlorocyclohexane
DDT	Dichlorodiphenyltrichloroethane
HCB	Hexachlorocyclo benzene
DDD	Dichlorodiphenyldichloroethane
DDE	Dichlorodiphenyldichloroethylene
SQG	Sediment quality guidelines
ERL	Effect range low
ERM	Effect range medium
TEL	Threshold effect level
PEL	Probable effect level
M-ERM-Q	Mean effects range median quotient
USEPA	United States Environmental Protection Agency
POP	Persistent organic pollutants
LADD	Lifetime average daily dose
HQ	Hazard quotient
ILCR	Incremental lifetime cancer risk

41.1 Introduction

Pesticides are the natural or synthetic chemicals intended to control various agricultural insects & pests, weeds and diseases (Ballantyne and Marrs 2004). According to the target pest, they can be classified as insecticides, weedicides, fungicides, rodenticides, etc. (Akashe et al. 2018). Among the various chemical classification, organochlorines (OCPs), organophosphorus (OPs), synthetic pyrethroids (SP) and different inorganic chemicals are the most important class of pesticides (Akashe et al. 2018). Pesticides have been used for decades to boost agricultural growth and almost one-third of the agricultural production solely depends on the use of synthetic pesticides (Zhang et al. 2011). An estimate indicates that without the use of pesticides, there will be almost 78%, 54% and 32% of crop losses for fruits, vegetables and grains, respectively (Cai 2008). India is one of the world's largest growing economy and with rapid growth in agricultural and industrial sectors;

pesticide consumption became inevitable to fulfil the ever-increasing food demand for its 1.3 billion population (Shagdhar and Rai 2019). India is the fourth largest global producer of agrochemicals and its per hectare consumption (0.6 kg/ha) of pesticides is far below the other countries. Around 295 pesticides molecules are registered for use in India (CIB and RC 2020).

Despite the beneficial influence of pesticide due to its contribution to increasing food production, extensive usage of them may pose risk to human and environmental health (Rani et al. 2020). Most of the pesticides applied in the agricultural and other sector are get accumulated in the soil after application (Hiltbold 1974). Their discrete and repeated application leads to an increase in accumulation. Pesticides like OCPs are highly persistent and though they have been banned long back, their residues are still present in agricultural (Chakraborty et al. 2017), urban (Kumar et al. 2018) and even in Himalayan and forest soil (Mishra et al. 2013; Devi et al. 2015). The reason is their uses in the public health sector as well as illegal uses. Several studies in India and abroad reported the occurrence of presently used and even banned pesticides in the soil matrix. However, a comprehensive compilation of these reports particularly in Indian soil environment is scarce due to the variation in the aim of different studies, differences in selection of pesticides and suitable extraction methodologies, regional and local differences which prevents from establishing a comprehensive overview. An extensive study by Chakraborty et al. (2015) indicates that soils of almost all the major cities of India are contaminated with pesticides. High levels of hexachlorocyclohexane (HCH) have also been found in soils from obsolete pesticide dumping sites (Jit et al. 2011). Traces of pesticide were also detected in forest soil of northeastern states of India (Mishra et al. 2013; Devi et al. 2015).

Alike soil in the terrestrial environment, sediment in the aquatic environment is the ultimate sink for pesticides. Due to presence of organic/inorganic particle and detritus, like soil, sediment is also highly heterogeneous and as a result, it can accumulate a large number of pesticides having different physicochemical properties (Yadav et al. 2015). Sometimes sediment also acts as a source of pesticide pollution for overlying water as it can release the accumulated pesticides under favourable condition. They can act as secondary sources of pesticides which can impart an adverse effect on sediment-dwelling organisms including fishes (Cui et al. 2020). River and lake sediments are the major sink of pesticides used in agricultural and urban soil. Still, the DDT (dichlorodiphenyltrichloroethane) and HCH can be detected in the sediment of Indian aquatic bodies (Kurakalva and Aradhi 2020). The above information indicates that the pesticide contamination in soil and sediment of India should be judged with grave concern because pesticide contamination will not only hamper the sediment/soil-dwelling organisms, but it will ultimately affect human health. Even though the consumption of pesticides in India is lower than the other Asian and Western countries, indiscriminate usage pattern resulted in their frequent occurrence in the soils and sediment (Sai et al. 2019).

In this chapter, we have summarized the occurrence, distribution, sources of pesticides in the soil and sediment environment of India and associated human and aquatic health risk assessment. Though India is considered as a hotspot of pesticide contamination, to derive any conclusion, it is necessary to through and critically analyse the available information related to pesticide contamination in soil and sediment and risk assessment. It is also necessary to suggest suitable remediation measures to overcome this burden. With this, the present endeavour aims to document the pesticide contamination in soil and sediment of India and its correlation with the history of usage. Here we have also described the impacts of pesticide contamination and threat associated with the indiscriminate use of pesticides which may help to restore the contaminated soils. This chapter also describes the recent development of novel soil remediation measures which can be effectively used to control the level of pesticide contamination.

41.2 Pesticide Production and Consumption in India

Continuous food supply to the growing Indian population has been a challenge to the Indian farming community. Tropical-humid climatic conditions are favourable for pest and disease attack on agricultural production system. The damage can go up to 35–40% on standing crops, while around 35% loss may occur during post production process (Dhaliwal et al. 2015). Some reported a loss of INR 14 lakh crores due to pest and disease attack in Indian agricultural system (Kumar and Gupta 2012). In the early 1960s the major crop losses were 25, 18, 10 and 10% for fruits, cotton, rice and sugarcane, respectively. To control the crop loss, use of plant protection chemicals/pesticides has emerged as one of the best practices with immediate effect. However, the crop loss scenario has changed since 2000, and cotton (30–50% loss) leads the series followed by rice, maize and oilseeds (25% each), sugarcane (20% loss) and groundnut (15% loss). Studies have indicated an increase in crop loss in post-green revolution time than pre-green revolution even after pesticide applications which could be due to climate change, change in cropping pattern, resistance development in pests, secondary outbreaks, etc. (Dhaliwal et al. 2007). Hence, the need for pesticides has increased over the past few decades. India consumes around 0.5 kg pesticides per ha, which is much lower than countries like the USA (4.5 kg/ha), Korea (6 kg/ha) and Japan (12 kg/ha). Out of total global production of pesticides (2 million tons/year), India consumes only 3.57%. In India, out of total 16.7 million ha of cultivated lands, only 25% receive pesticide application, but it has created havoc in the environment. In India, the pesticide use pattern is 65% insecticides, 16% herbicides, 15% fungicides and 4% others (Devi et al. 2017). In India nearly 67 and 8.5% of total consumed pesticides are used in agricultural-horticultural production system and public health sector, respectively (World Bank 1997). The major pesticide consuming crops are cotton (40–50%), followed by rice (20%), vegetables and fruits (13–24%), coarse grains and oilseeds (6–7%) and sugarcane (2–3%). But area-wise coarse grains and oilseeds cover 58% of cropped area, followed by rice (24%), vegetables and fruits (18%), cotton (5%) and sugarcane (2%) (Abhilash and Singh 2009). Out of various pesticide groups, organochlorines (OC) contribute 40% in Indian scenario. However, in the last decade OP has emerged as the dominant pesticide over the OCPs. Consumption of carbamates and SP is also shooting up. The total pesticide production in India has

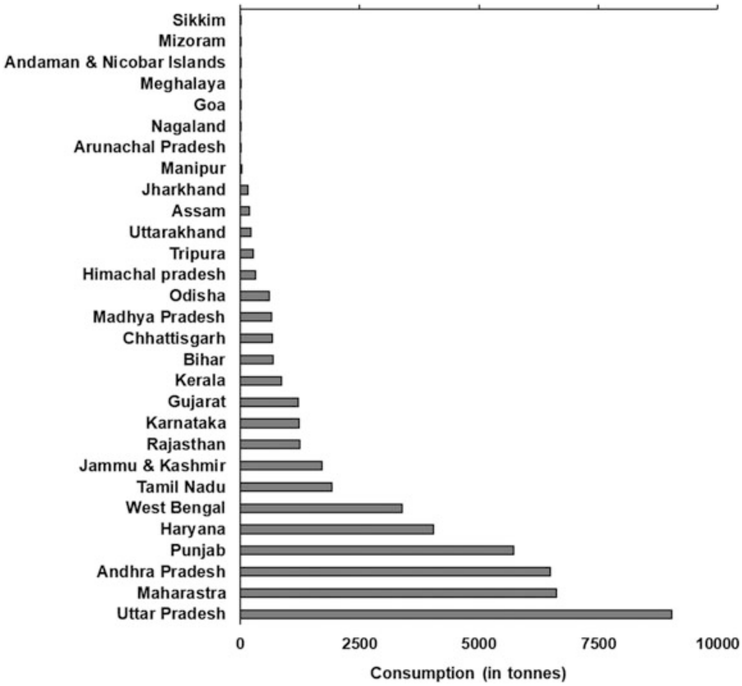

Fig. 41.1 Pesticide consumption in various states of India (2012–2013)

been found to be stagnant around 80,000 tons since 2005–2006. However, the annual pesticide consumption showed an increasing trend from 39,773 tons in 2005–2006 to 52,980 tons in 2011–2012. Pesticide consumption is different for every state of India due to variation in cultivation practices (Devi et al. 2017). Uttar Pradesh (9035 tons), Maharashtra (6617 tons), Andhra Pradesh (6500 tons) and Punjab (5725 tons) are the maximum pesticide-consuming states, followed by Haryana (4050 tons) and West Bengal (3390 tons). The northeastern states like Meghalaya, Sikkim, Nagaland, Manipur, Mizoram and Arunachal Pradesh and the southern state of Goa consume very less amounts of pesticides (less than 100 tons each). The remaining states (Assam, Jharkhand, Chhattisgarh, Bihar, Odisha, Madhya Pradesh, Uttarakhand, Himachal Pradesh and Kerala) showed the pesticide consumption between 100 and 1000 tons (Fig. 41.1). However, the trend analysis of pesticide consumption per ha revealed a new entrance by the state of Jammu and Kashmir (2.34 kg/ha), followed by Punjab (1.37 kg/ha) and Haryana (1.15 kg/ha). Most of the states from North-East India were found to use very low amount of pesticides (below 0.10 kg/ha). The overall domestic consumption of pesticide in India showed a negative trend during 2000–2013. However, the trend of pesticide consumption per ha during 2000–2013 showed a positive growth in 17 out of 29 states of India (Fig. 41.2). The top three states with a positive growth rate are Jammu and Kashmir (100.22%) > Andaman and Nicobar Islands (17.85%) >

Fig. 41.2 State-wise pesticide usage scenario in terms of compound annual growth rate (%) during 2000–2013

Tripura (9.21%). Whereas, 12 states showed negative growth rate and the order of top three states is Mizoram (−7.53%)< Gujarat (−6.24%) < Assam (−6.08%). Even a productive state like Punjab showed a negative growth rate of −2.23%.

However, value-wise pesticide order in India is OPs (over 50%) > SP (19%) > OCPs (16%) > carbamates (4%) > botanicals and others (1%). The most commonly used pesticides in India include phorate (OP, toxicity—extremely hazardous), monocrotophos (OP, toxicity—highly hazardous), combined mixture of profenofos and cypermethrin (OP + SP, toxicity—highly hazardous), phosphomidon (OP, toxicity—extremely hazardous), carbofuran (C, toxicity—highly hazardous), edifenphos (F, toxicity—moderately hazardous), imidacloprid (OP, toxicity—moderately hazardous), triazophos (OP, toxicity—moderately hazardous), fenvalerate (SP, toxicity—moderately hazardous), alphamethrin (SP, toxicity—moderately hazardous), dimethoate (OP, toxicity—moderately hazardous), quinalphos (OP, toxicity—moderately hazardous), endosulfan (OC, toxicity—moderately hazardous), carbaryl (C, toxicity— moderately hazardous), chlorpyrifos (OP, toxicity—moderately hazardous), cyhalothrin (SP, toxicity—moderately hazardous), fenthion (OP, toxicity—moderately hazardous), DDT (OC, toxicity—moderately hazardous), lindane (OC, toxicity—moderately hazardous), malathion (OP, toxicity—slightly hazardous), acephate (OP, toxicity—slightly hazardous), carbendazim (C, toxicity—slightly hazardous), atrazine (triazines, toxicity—slightly hazardous), etc. Out of various pesticides, lindane, DDT and malathion constitute more than 70% of Indian pesticide consumption. Though agricultural application of lindane, DDT, endosulfan, etc. has been stopped, illegal application through spurious pesticides has become a grave matter of concern. Application of DDT in public health sector to control malaria is also a source of environmental pollution. Huge quantities of DDT are still used in India. For instance, in 2001, about 3750 tons of DDT was used under National Malaria Programme in rural and urban residential areas (Gupta et al. 2016). Further non-judicious and indiscriminate uses of pesticides are very common found malpractices India (Shetty 2004). For example, 15 number of pesticide sprays were found instead of recommended 8 sprays in rice-cultivating areas of Raichur and Bellary, Karnataka. Similarly, 20–30 spays in cotton were found instead of recommended 15 sprays in cotton-growing areas of Guntur and Warangal, Andhra Pradesh. Whereas, 15–20 sprays can be observed instead of recommended 10 sprays for cotton in Bathinda, Punjab. Farmers give 15–20 sprays instead of recommended 10 sprays for cole-crops in Nasik, Maharashtra. Indiscriminate uses of pesticides have resulted in development of pest resistance (Agnihotri et al. 1999), pest-resurgence (Dudani 1999), secondary outbreak (Puri et al. 1999), etc., which lead to increase in crop losses. As a result, farmers are applying more pesticides than the usual practices to control the pests, and unknowingly contaminating the environment.

41.3 Entry Route and Pesticide Biogeochemistry in Soil

Soil acts as the major sink for applied pesticides. Nearly 10% of applied pesticides reach their targets, and majority (70–90%) of applied pesticide come to soil as indirect application. Further, pesticides like fumigants, nematicides, herbicides, etc. applied to soil directly contribute to pesticide sink of soil. Once a pesticide molecule reaches soil, its fate is determined by the properties of soil, pesticide and climatic conditions (Wauchope et al. 2002). The major processes involved in determination of pesticide's fate are adsorption, desorption, leaching, volatilization and degradation. The probable pathways involved in pesticide dynamics in soil are presented in Fig. 41.3. Directly or indirectly pesticides come to soil and get adsorbed onto the soil. Soil textural class plays a significant role in determining pesticide's adsorption (Baskaran et al. 1996). Adsorption of a pesticide molecule is directly related to the clay and oxide/hydroxide contents of the soil (Sarkar et al. 2018). The clay surfaces and oxides/hydroxides possess negative charges and hence easily adsorb cationic pesticides (paraquat, diquat, triazines, anilines, anilide herbicides, etc.) via electrostatic attraction/van der Waals forces. The nature of clay also influences the adsorption of pesticide molecules and the adsorption order is nontronite > montmorillonite > illite > kaolinite (McConnell and Hossner 1985). Further, surface/interlayer saturation of clays with various ions also influences the pesticide adsorption and ease of adsorption is in the order of $K^+ > Na^+ > NH_4^+ > Ca^{2+} > Mg^{2+}$ (Weissmahr et al. 1999). Increase in sand/silt contents in soil shows

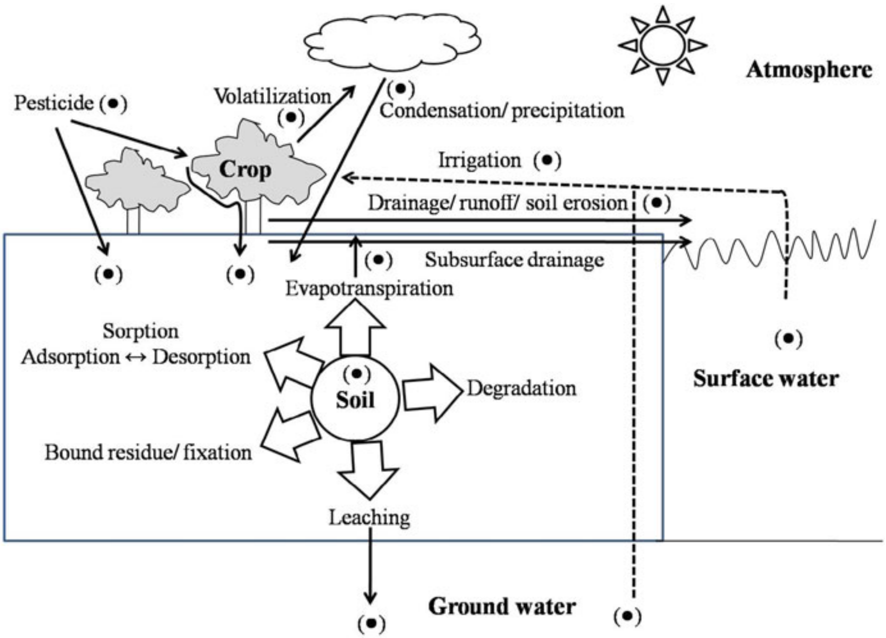

Fig. 41.3 Tentative pathways related to fate of pesticide in soil

less adsorption of pesticides. A soil/solution distribution coefficient (K_d) has been widely used to indicate the sorption behaviour of pesticides. Higher the K_d value indicates higher adsorption onto the soil and hence less availability in solution phase for leaching/degradation. For example, Propargite with a K_d value of 107 is more strongly adsorbed in soil than the Rimsulfuron with K_d value of 0.87 (Weber et al. 2004). However, soil organic matter (SOM) plays more significant role in adsorption of pesticides. Higher SOM results in higher adsorption of pesticides via ligand exchange, H-bonding, charger-transfer bonds between the pesticide and SOM (Sadegh-Zadeh et al. 2017; Senesi et al. 2001). SOM acts as a potent adsorbing site for charged/polar/non-polar pesticides. Hence, the organic carbon normalized sorption coefficient (K_{oc}) gives a better picture of pesticide adsorption than K_d and higher value indicates more adsorption. Soil pH influences the ionization of clays/SOM surfaces and the pesticide molecules. For anionic pesticides, decrease in soil pH results in an increase in adsorption due to decrease in negative charges of the adsorption sites of clays/SOM, for example bromoxynil (Sheng et al. 2005), glyphosate (McConnell and Hossner 1985), etc. Further, soil properties like water content, temperature, etc. significantly influence the pesticide sorption onto soil. The basic properties of pesticide molecules like water solubility, valour pressure, pK_a or pK_b value, K_{ow} (octanol-water partition coefficient), groundwater ubiquity score (GUS), etc. also influence the adsorption behaviour onto soil. Table 41.1 presents the fate of pesticide in relation to soil and its own property. The highly adsorbed pesticides are less available for leaching/degradation process, hence they often form bound residues and may become a persistent contaminant. Once pesticide molecule comes in soil solution it undergoes either leaching or degradation. Degradation can be physico-chemical or microbial or sometimes a combination of both. Degradation may result in formation of non-toxic and sometimes, toxic metabolites as well. Figure 41.3 shows a probable movement of pesticide molecule in various components of environment. Pesticides may come to a virgin soil by the processes of drift, pesticide adsorbed soil particles with drainage water or surface run-off, pesticides dissolved in subsurface drainage water, and even pesticides may come with the rain/precipitation. Irrigation with contaminated surface water/groundwater may also cause accumulation of pesticides in soil. Moreover, local climatic conditions, mainly temperature and precipitation, influence these reactions between soil and pesticide. Higher precipitation results in more dissolution of highly soluble pesticides and resulting in lower adsorption and high pesticide leaching. Similarly, in dry seasons, pesticides with high vapour pressure show evaporation losses from soil and more concentration in soil water. The total processes responsible for the fate of pesticides are complex and dynamic. Therefore, a pesticide residue gets stored in soil and moves from soil to water/air and continues its pollution cycle. Therefore, growing crops/raising animals in pesticide-contaminated soil poses a serious challenge of bioaccumulation and biomagnifications of pesticide residues in higher organisms.

Table 41.1 Properties of soil and pesticides related to fate of pesticide

	Soil processes					
Soil properties	Adsorption	Desorption	Volatilization	Leaching	Degradation	Persistence
Clay content (↑), K_d↑	↑	↓	↓	↓	↓	↑
Sand and silt content (↑)	↓	↑	↑	↑	↑	↓
Organic matter content (↑), log K_{oc} ↑	↑	↓	↓	↓	↓	↑
Soil temperature (↑)	↓	↑	↑	↑	↑	↓
pH $>$pK_a pH $<$pK_a	↓ ↑	↑ ↓		↑ ↓		
Soil water (↑)	↓	↑	↓	↑	↓	↓
Pesticide properties						
Water solubility (↑) High: $>$500 mg/L; moderate: 50–500 mg/L; low: $>$50 mg/L	↓	↑	↓	↑	↓	↓
Log K_{ow} (↑) High accumulation: $>$3; moderate: 2.7–3; low: $<$2.7	↑	↓	–	↓	↓	↑
GUS index (↑) Highly leachable: $>$2.8; moderate: 1.8–28; low: $>$1.8	↓	↑	–	↑	–	↓
Vapour pressure (mPa) (↑) Highly volatile: $>$10; medium: 5–10; low: $<$5	↓	↑	↑	↓	–	↓

41.4 Occurrence and Distribution of Pesticides in Soil and Sediment of India

41.4.1 Pesticide Occurrence in Agricultural Soils of India

India is the fourth consumer of global pesticides. India holds a production capacity of 139,000 tons/year, though its production revolves around 80,000 tons/year over the past 15 years. India's total pesticide consumption is around 40,000 tons. In India, nearly 67% of total consumed pesticides are used in the agricultural or horticultural production system (World Bank 1997). Quantity-wise contribution by various pesticides follows this order: OCPs (40%) > OPs (30%) > carbamates (15%) > SP (10%), botanicals and others (5%). Quantity-wise DDT, HCH and monocrotophos contribute over 70% of total pesticides. Even endosulfan alone contributes 10% of the total pesticide consumption in India. Due to high efficiency, broad-spectrum applicability and low cost, OCPs have been used in agriculture. However, due to toxicity, persistence, lipophilicity, long-distance transportability and ill-effects on a wide range of organisms including human, application of several pesticides in agriculture has been either banned or restricted in India. The half-life of various OCPs is as follows: p,p′-DDT: 20 years, o,p′-DDT: 15–20 years, lindane: 3–4 years, technical HCH: 2.7–22.9 years, heptachlor: 2 years, aldrin: 5 years, dieldrin: 5 years, endrin: 12 years, chlordane: 189 days, etc. In India, DDT was banned for agricultural applications since 1985; however, its application in the public health sector to eradicate malaria is still permitted since 1989. Till date, over 100,000 tons of DDT has been used in India, mostly for agricultural purpose and malaria prevention (Abhilash and Singh 2009; Arora et al. 2013). Application of aldrin, chlordane and heptachlor has been stopped since September 1996. Whereas, the use of endrin and dieldrin in agriculture has been stopped since May 1990 and July 2003, respectively. Application of technical HCH in agriculture has been banned since April 1997. Use of endosulfan and methoxychlor is restricted for use in Indian agriculture (Pandey et al. 2011; UNEP 2003). Hexachlorocyclo benzene (HCB) has never been registered as a pesticide in India, but still it represents over 30% of total pesticide consumption in India (Yadav et al. 2015). Though the direct and legal application of these pesticides has been stopped nearly 15–35 years back, by the time of their banning, million tons of these pesticides have been used in Indian agriculture. That is why still the residues of these pesticides or their metabolites are found in Indian agricultural soil. Application-wise, DDT tops in the list of OCPs in India. The technical DDT contains ~75% p,p′-DDT, ~15% o,p′-DDT, ~4% p,p′-DDE and other isomers/transformed products. In soil, p,p′-DDT gets easily converted into o,p'-DDT (Talekar et al. 1977). Under anaerobic condition, p,p′-DDT gets converted into DDD (dichlorodiphenyldichloroethane) by reductive dechlorination and DDD gets easily converted to p,p′-DDE (dichlorodiphenyldichloroethylene) via the process of dehydrochlorination (Hao et al. 2008). Moreover, p,p′-DDT gets converted to p,p′-DDE under the aerobic condition with UV light exposure during prolonged exposure in soil (Atlas and Giam 1988; Baxtor 1990). Therefore, the ratio of various metabolites has been used to predict the source and exposure time of DDT application. The ratio of p,p′-DDT to ∑DDT with a value 0.77 indicated a fresh application of technical DDT. Otherwise, a value of less than 0.77 represents an old application of DDT (WHO 1989). Similarly, a ratio value of p,p′-DDT to p,p′-DDE lesser than 0.33 indicated aged/old application of DDT. Further, a ratio value of (p,p′-DDT/p,p′-DDE + p,p′-DDD) more than 1 indicates the recent application of DDT and a value less than 1 represents the aged application of DDT (Li et al. 2008). Further, the ratio of o,p′-DDT to p,p′-DDT can be used to predict the nature of applied DDT. A ratio value within 0.2–0.26 indicates the application of technical DDT, whereas a value ~7.5 indicates the application of dicofol-DDT (Qui et al. 2005). Similarly, detailed information of the popularly used HCH can be predicted from variations of its isomers. There are two forms available in India: technical HCH (banned in 1997) and lindane. The technical HCH contains 55–80% α-HCH, 5–14% β-HCH, 8–15% γ-HCH, 2–16% δ-HCH, 3–5% ε-HCH, whereas lindane contains mostly γ-HCH (>90%). Under sunlight exposure, γ-HCH gets also converted to α-HCH in soil and similar transformation can be observed with soil microbial activities (Malaiyandi and Shah 1980). However, both α- and γ-HCH get converted to β-HCH (Walker 1999), which is the most thermodynamically stable HCH isomer with low vapour pressure and solubility (Chen et al. 2005). Hence, a ratio of α-HCH to γ-HCH can predict the source and time of HCH application. A value of 3–7 represents a fresh application of technical HCH (Yang et al. 2008), whereas a value less than 1 indicates the use of lindane (Willet et al. 1998). Presence of higher amount of β-HCH indicates ageing of applied HCH or lindane. In the case of endosulfan, α- and β-isomers are present in a ratio of 7:3. The α-endosulfan gets easily converted to more stable β-endosulfan which is less soluble and strongly bound to soil (Beyers et al. 1965). Under the aerobic condition, both α- and β-isomers can be transformed to endosulfan sulphate. Presence of higher amount of β-endosulfan indicates ageing of applied technical endosulfan. A ratio of α-/β-endosulfan more than 2.33 indicates a fresh application and a smaller value (<2.33) denotes the historical application of endosulfan. Whereas, a ratio value of cis- to trans-chlordane more than 1 indicates historical applications. Similarly, aldrin gets oxidized to more stable and persistent dieldrin. Application of aldrin is banned in India, hence the presence of dieldrin indicates residues from aged/historical application of aldrin. Apart from OCPs, OPs, SP, carbamates, etc. are less persistent in soil and pose less pollution problems. Hence, the contaminated soils have been reported to act as a reservoir and re-emitter of these persistent pesticides (Devi et al. 2011; Gong et al. 2010; Pozo et al. 2011). Table 41.2 presents the pesticide residue scenario in some of the agricultural soils of India.

41.4.1.1 Pesticide Residues in Agricultural Soils of Northern and Western India

Singh (2001) reported frequently (>90% sample) found OCPs (∑DDT, ∑HCH, aldrin, dieldrin) in agricultural lands of Agra from the state of Uttar Pradesh. Heptachlor and endosulfan were detected in 60% samples but without any trend. The agricultural application of DDT/HCH through spurious pesticides/illegal

Table 41.2 Pesticide residues in agricultural soils from various parts of India and world

Location	∑DDT (major isomer)	∑HCH (major isomer)	∑endosulfan (major isomer)	Reference
North and West India				
Agra, Uttar Pradesh	1.01 (pp-DDT)	0.5 (α-HCH)	0.03 (β-endosulfan)	Singh (2001)
Hisar, Haryana	1–66 (pp-DDE)	2–51 (γ-HCH)	2–39 (β-endosulfan)	Kumari et al. (2008)
Aligarh, Uttar Pradesh	34 (op-DDT)	88.9 (α-HCH)	–	Nawab et al. (2003)
Delhi, Haryana, Uttar Pradesh, and Rajasthan	0.01–15.79 (pp-DDE)	0.01–104.14 (α-HCH)	0.01–7.57 (β-endosulfan)	Kumar et al. (2012)
Southern India				
Kasimedu, Tamil Nadu	0.1 (pp-DDT)	0.1 (α-HCH)	<0.05	Senthilkumar et al. (2001)
Ennore, Tamil Nadu	35 (pp-DDT)	2.1 (β-HCH)	<0.01	
Cochin, Kerala	3.8 (pp-DDT)	4.8 (β-HCH)	0.2	
Visakhapatnam, Andhra Pradesh	0.1 (pp-DDT)	0.21 (β-HCH)	0.12	
Idukki, Kerala	Nd-52.9 (pp-DDD)	Nd-52.6 (δ-HCH)	Nd-63.6 (β-endosulfan)	Joseph et al. (2020)
Thiruvallur, Tamil Nadu	0.9–10.3	0.9–75.3	–	Jayashree and Vasudevan (2005)
Northeastern India				
Nagaon, Assam	903 (pp-DDT)	825 (β-HCH)	–	Mishra et al. (2012)
Dibrugarh, Assam	757 (pp-DDT)	705 (β-HCH)	–	
Indian Himalayan region				
Assam, Arunachal Pradesh	0.28–2127 (pp-DDT)	0–2.79 (γ-HCH)	0–2.83 (β-endosulfan)	Devi et al. (2015)
Indian islands				
Andaman and Nicobar islands	0.23–12.22 (pp-DDT)	–	0.75–38.16 (endosulfan sulphate)	Murugan et al. (2013)
International scenario				
USA	211	0.52	–	Bidleman and Leone (2004)
North-East China	79.3	93.8	–	Wang et al. (2006)
South-East China	661	1.64	–	Jiang et al. (2009)

(continued)

Table 41.2 (continued)

Location	∑DDT (major isomer)	∑HCH (major isomer)	∑endosulfan (major isomer)	Reference
North-West Spain	–	336.8	–	Pereira et al. (2010)
Vietnam	110	4.8	–	Thao et al. (1993)
Shanghai	21.41	2.41	–	Jiang et al. (2009)

application could be a source of soil pollution. Further, crop irrigation with pesticide-loaded Yamuna river water could be a possible source of pesticide accumulation in agricultural soils of Agra. Potato is one of the major crops in that area where the application of aldrin, as anti-termiticide, is common and could be a possible reason of soil contamination (0.87 ng/g with a 98.3% frequency), and presence of dieldrin (0.33 ng/g with a 93.1% frequency) indicates degradation of previously applied aldrin in soil. There are some reports on high contamination of agricultural soils of Punjab, Delhi and UP with DDT and HCH to the tune of 675 and 32 ng/g soil (Anonymous 1988). Nawab et al. (2003) found that agricultural soils from Aligarh, Uttar Pradesh were with ∑DDT, ∑HCH and aldrin with a frequency of over 97%. The region is popular for vegetables and oilseed crops, and farmers are found to use OCPs even after banning of some pesticides. Presence of γ-HCH (47.35 ng/g) as a major component and α/γ HCH ratio of 0.82 indicated recent application of lindane, not the technical HCH. The o,p′-DDT (13.3 ng/g) was the major DDT isomer and o, p′-DDT/p,p′-DDT ratio of 3.64 indicated source as dicofol-DDT. The p,p′-DDT/∑DDT value of 0.12 indicated historical application of dicofol in the area. Aldrin was detected in all soil samples with a mean of 1.46 ng/g. Kumari et al. (2008) found OCPs, OPs and SP residues in agricultural soils of Hisar, Haryana. ∑DDT (p, p′-DDE major metabolite), ∑HCH (γ-HCH major metabolite) and ∑endosulfan (β-endosulfan major metabolite) along with chlordane (0.2–1.9 ng/g soil) were the commonly detected pesticides belonging to OCPs. Apart from OCPs, cypermethrin (1–35 ng/g soil) and fenvalerate (1–22 ng/g soil) belonging to synthetic pyrethroids and malathion (2–8 ng/g soil), quinalphos (1–10 ng/g soil), chlorpyriphos (2–172 ng/g soil), triazophos (1–10 ng/g soil) along with monocrotophos (up to 4 ng/g soil) and dimethoate (2 ng/g soil) from POs were also detected in some soil. However, the commonly found pesticides include DDT, cypermethrin and chlorpyriphos. These results indicated a shift in pesticide application pattern from OCPs to OPs and synthetic pyrethroids in Haryana. Kumar and Gupta (2012) found pesticide residues from vast agricultural lands of Delhi (Najafgarh, Nizamuddin Yamuna Bridge area, Alipur block and Kanjhawala block), Haryana (Ballabgarh, Faridabad and Sonipat districts), Uttar Pradesh (Baghpat, Gautam Budh Nagar and Ghaziabad districts) and Rajasthan. ∑HCH was the most frequently (>89% frequency) detected pesticide ranging from 0.01–104.14 ng/g soil. The α/γ HCH ratio was <0.01 to 8.83 which indicated mixed application of technical HCH and lindane.

The ∑DDT ranged from 0.01 to 15.79 ng/g. The ratio of p,p′-DDT/∑DDT and p,p′-DDT/p,p′-DDE values was 0.44 and 0.22 which indicated the historical application of DDT. The areas had not received any fresh application of DDT. Moreover, o,p′-DDT/p,p′-DDT value was 0.25 which indicated that historical application of technical DDT, not the dicofol-DDT. ∑endosulfan residues ranged from 0.01–7.57 ng/g and there was no α-endosulfan. Only β-endosulfan residues (0.01–7.57 ng/g) were present which indicated ageing of previously applied technical endosulfans. Again, detection of only dieldrin (0.01–2.38 ng/g) instead of aldrin indicated historical application of aldrin and there was no trend in soil residues. Kumar and Gupta (2012) also reported presence of some OP residues in the following order: chlorpyriphos (in 51.5% soils ranging from 0.01–31.7 ng/g) > phosphamidon (in 24.9% soils ranging from 0.01–20.95 ng/g) > monocrotophos (in 8.2% soils ranging from 0.01–3.92 ng/g) > quinalphos (in 7.7% soils ranging from 0.01–6.46 ng/g) > ethion (in 7.7% soils ranging from 0.01–6.46 ng/g). However, residues of other commonly applied OPs like profenophos, dimethoate, phorate, etc. were not detected in soils. Residues of some herbicides were also reported by the team in the order of pendimethalin (in 61% soils ranging from 0.03–1.28 ng/g) > butachlor (in 36% soils ranging from 0.02–1.22 ng/g) > fluchloralin (in only 3% soils ranging from 0.01–0.25 ng/g). This study indicated a shift in pesticide application in North Indian soils as OPs, synthetic pyrethroids or carbamate group of pesticides were replacing OCPs.

41.4.1.2 Pesticide Residues in Agricultural Soils of Southern India

Several studies have indicated the presence of pesticide residues in agricultural soils of south India. Senthilkumar et al. (2001) found OCPs, namely ∑DDT, ∑HCH and HCB in agricultural soil of Ennore and Kasimedu (Chennai, Tamil Nadu), Cochin (Kerala) and Visakhapatnam (Andhra Pradesh) from southern parts of India. β-HCH and p,p'-DDT have commonly encountered residues with 75.3 and 80% frequency and occurrences of these stable isomers indicated residues from old applications. Though HCB is not a registered pesticide, it was commonly detected in all soils (concentration range <0.01 to 0.2 ng/g) due to indiscriminate use of pesticides. Recently, Joseph et al. (2020) reported the presence of OCPs in south Indian agricultural soils of cardamom hills of Idukki, Kerala. Endosulfan was the most frequently (in 33% soils) detected residue ranging from 0–63.6 ng/g and β-endosulfan was the dominating isomer (0–49.9 ng/g). α-endosulfan and endosulfan sulphate varied from 0–8.5 to 0–5.2 ng/g. Drin-related compounds were observed in 31.4% soils. Endrin along with endrin aldehyde was frequently detected in the range of 0–35.6 and 0–32.1 ng/g, which indicated fresh application of endrin. Whereas, dieldrin was detected in 5.5% soils in the range of 0–35.6 without detection of aldrin, which indicated the historical application of aldrin. ∑DDT was detected in 20.3% of soils within the range of 0–52.9 ng/g. p,p′-DDD (nd-43.6 ng/g) was the major DDT isomer. The ratio of (p,p′-DDT/p,p′-DDD+p,p′-DDE) values was below 1, which indicated the historical application of DDT. Whereas, ∑HCH was detected in 15.4% soils. δ-HCH was the dominant isomer with a concentration range of 0–16.5 ng/g, which indicated the historical application of technical HCH.

41.4.1.3 Pesticide Residues in Agricultural Soils of Northeastern and Himalayan Region of India

Pesticide residues have been detected in northeastern states and Himalayan region of India also. Mishra et al. (2012) reported the presence of OCPs in various agricultural soils of northeastern India, specifically from the Nagaon and Dibrugarh districts of Assam. The concentration of ∑DDT and ∑HCH were 166–2288 and 98–1945 ng/g in Nagaon and 75–2296 and 178–1701 ng/g in Dibrugarh, respectively. pp-DDT (8–1478 and 8–1199 ng/g in Nagaon and Dibrugarh, respectively) was a major component than p,p′-DDE (11–1159 and 4–1187 ng/g in Nagaon and Dibrugarh, respectively). The tea garden soils had more pp-DDT and paddy soils were dominated with pp-DDE. The ratio of (p,p′-DDT/p,p′-DDD+p,p′-DDE) values was ranging from 0.03–39.96 and 0.05–14.76 for Nagaon and Dibrugarh, respectively, which indicated a mixture of historical and fresh application of DDT. Almost 73% of soils received a fresh application of DDT, whereas only 27% showed the historical application of DDT. Further, HCH was detected in all types of agricultural soils and β-HCH was the dominant isomer (detected in 100% soils) followed by γ-HCH (detected in 97% soils). In the tea garden soils, γ-HCH was the dominant HCH residue, whereas β-HCH was main HCH isomer in paddy soils. The ratio of α/γ HCH ratio was <0.01–29.7 and <0.01–21.9 in Nagaon and Dibrugarh, respectively, which indicated mixed application of technical HCH and lindane. This indicated the non-judicious application of HCH and illegal application of DDT in agricultural soils of North-East India (Imphal Free Press 2008). Pesticide residues in agricultural soils of Indian Himalayan region of Assam (Guwahati, Tezpur and Dibrugarh) and Arunachal Pradesh (Itanagar) have been reported by Devi et al. (2015). ∑DDT was detected in the range of 0.28–2127 ng/g and p,p′-DDD (mean-148 ng/g) was the major DDT isomer. Even the concentration of ΣDDT was several folds higher than reported in Monte Legnone, Italy (2.2 ng/g) (Tremolada et al. 2008) and Ruoergai highland, China (1.63 ng/g) (Gai et al. 2014). The ratios of (p,p′-DDT/p,p′-DDD+p, p′-DDE) values were above 5, which indicated a fresh application of DDT. The ratio of o,p′-DDT/p,p′-DDT was around 0.24, which indicated on-going applications of technical DDT, not dicofol (except Itanagar, Arunachal Pradesh). High level of DDT could be due to high application of DDT in tea garden (Devi et al. 2013a, b), coupled with atmospheric transport from intensive agricultural states like West Bengal (Chakraborty et al. 2010). ∑HCH was detected in the range of 0–2.79 ng/g and γ-HCH was the dominant isomer. The α/γ HCH ratio was 0.27–0.39, which indicated the use of lindane, with limited use of technical HCH. The ratio of α/β endosulfan values was below 2.33 in Itanagar, Tezpur and Guwahati, which indicated fresh application of endosulfan. Whereas, the ratios of α/β endosulfan were above 2.33 for Dibrugarh, indicating the historical application of endosulfan. Aldrin, dieldrin and endrin were detected at very low concentrations (below 3 ng/g) which could be due to either historical application or global atmospheric transport of OCPs. Cis/trans-chlordane ratios were below 1, which indicated a fresh application of chlordane in these agricultural soils.

41.4.1.4 Pesticide Residues in Agricultural Soils of Indian Islands

Murugan et al. (2013) reported pesticide residues from agricultural soils of Andaman and Nicobar islands of India. Endosulfan and DDT were detected in 41.7% soils, followed by aldrin (16.7%) and fenvalerate (8.3%). ∑DDT was detected in the range of 0.23–12.22 ng/g and p,p'-DDT was the dominant DDT isomer. The ratios of (p, p′-DDT/p,p′-DDD+p,p′-DDE) values were above 1, which indicated fresh application of technical DDT in island soils. The total endosulfan residue was in the range of 0.75–38.16 ng/g and endosulfan sulphate was the dominant isomer. The dominance of endosulfan sulphate indicated historical application of endosulfan. Residues of synthetic pyrethroids, mainly fenvalerate-l (0–3.96 ng/g) and fenvalerate-ll (8.3–19.17 ng/g) were detected in soils. The study indicated the application of alternative pesticides to OCPs in island agricultural system.

Hence, it can be concluded that OPCs are present across various agricultural soils of different agro-climatic zones of India. OPs, synthetic pyrethroids and carbamate pesticides are substituting the OCPs. However, non-judicious and illegal application of banned pesticides is a serious issue in Indian agriculture.

41.4.2 Residues of Pesticides in Virgin Soil of India (Forest Soils, Wetland Soils, Soils from Unused Land or Fallow Land)

Persistent pesticides like OCPs through distance transport can reach remote areas like the Arctic, Antarctic and Tibetan plateau (Houde et al. 2019; Casal et al. 2019; Gai et al. 2014). Studies also indicate that pesticides can be detected in soils of forestland (Devi et al. 2013a, b), Himalayan region (Devi et al. 2015), where there is no history of pesticides used. Compared to agricultural, industrial and urban soil, forest soil can be considered as virgin soil regarding the level of pesticides used. However, due to higher organic matter content, they act as an ultimate sink of pesticides (Moeckel et al. 2008).

Murugan et al. (2013) reported pesticide residues in the soil of Andaman having different land uses including in mangroves and forest soil. Though pesticides were detected in the coastal plains and agricultural soil, however, insignificant amount of pesticides was detected in mangrove soil and forest soils. In contrast, soil microbial biomass carbon, an important soil health indicator was highest in forest soil followed by mangrove soil. Similarly, Bishnu et al. (2008) could not find any traces of pesticides in forest soil adjacent tea garden soils, while pesticides like ethion, chlorpyriphos and endosulfan were detected in various tea garden soils. In addition to this, soil microbial activities and enzymatic properties were lower in soils of tea garden as compared to forestland. However, Devi et al. (2013a, b) observed slight contamination of HCHs, DDTs and endosulfan in surface soil collected from the forest, grassland, wildlife sanctuary and wetland areas of northeastern (Tripura, Manipur and Assam) states of India. Significant correlation among the different pesticides and their metabolites indicates a similar source of pollution and possibly may be the agricultural uses. Even, contamination of OCPs is also reported in a network of protected areas like wetland (Nag et al. 2020), wildlife sanctuary and national park (Kathpal et al. 2004; Bhadouria et al. 2012). The sediment of Keoladeo National Park (Bharatpur, Rajasthan) also reported to be contaminated with OCPs (Bhadouria et al. 2012). OCP concentration in the sediment of inside the park varied from 0.12 mg/kg (dieldrin) to 5.55 mg/kg (γ-HCH), while outside the park it ranged from 0.125 mg/kg (p,p′-DDD) to 7.54 mg/kg (γ-HCH), though most of the pesticides detected in different studies are at or below the alarming level. But since these systems are supporting a large amount of flora and fauna, continuous accumulation of pesticides may be harmful on a long-term basis.

41.4.3 Pesticide Pollution in Urban and Peri-urban and Industrial Areas of India

With the fast population growth and rapid urbanization, health risk associated with the urban surroundings is of grave concern (Fernandes et al. 2020). Though the pesticide contamination in agricultural soils is well studied along with their ecological risk, the study related to the status and risk assessment of urban soil regarding the pesticide pollution is very limited. In reality, pesticide biogeochemistry in urban soil is different from the agricultural soils due to unique physicochemical properties (Cohen 2010) of an urban area which consists of agricultural, industrial, residential area along with the urban lake. There are various routes of exposure of urban soil to pesticides (Fig. 41.4) which may transfer to the human being through various routes (ingestion, inhalation, dermal, etc.). Moreover, pesticide application in urban soil is more diverse as compared to agricultural soil. Starting from the kitchen garden to public places, institution, there are various means of application of pesticides in urban areas for controlling urban pest (Meftaul et al. 2020). For example, though DDT and HCH are banned in India, still they are used for city malaria control programs (Kasinathan et al. 2019) and reports are available where they are detected in urban soils of India (Chakraborty et al. 2017). During production, transportation and storage also pesticides can enter into the urban environment (Relyea 2005). Improper disposal of empty pesticide containers in waste dumping sites in urban areas may also be the source of pesticide pollution. Widespread pesticide use in urban and peri-urban agriculture and their drifts may also contaminate the urban soil (Ramakrishnan et al. 2019). Atmospheric deposition and distance transport may be another source (Chakraborty et al. 2015). Recently peri-urban vegetable cultivation is increasing day by day to meet the vegetable demand of a large population of urban areas and high pesticide input may pose the potential human health risk. Study indicates pesticide use in peri-urban vegetable cultivation is comparatively higher than those grown in rural areas (Querejeta et al. 2012; Chourasiya et al. 2015; Margenat et al. 2019).

As compared to agricultural soils, the status of pesticide pollution in urban soils of India is very limited. Most of the study concentrated on OCPs and more particularly DDT and HCH. Way back in 1988 and 1989, Kawano et al. (1992) surveyed a wide variety of agricultural and urban soil for assessing the OCP level. The residue levels of OCPs were found to be higher in agricultural soil than urban soil. Recently, high

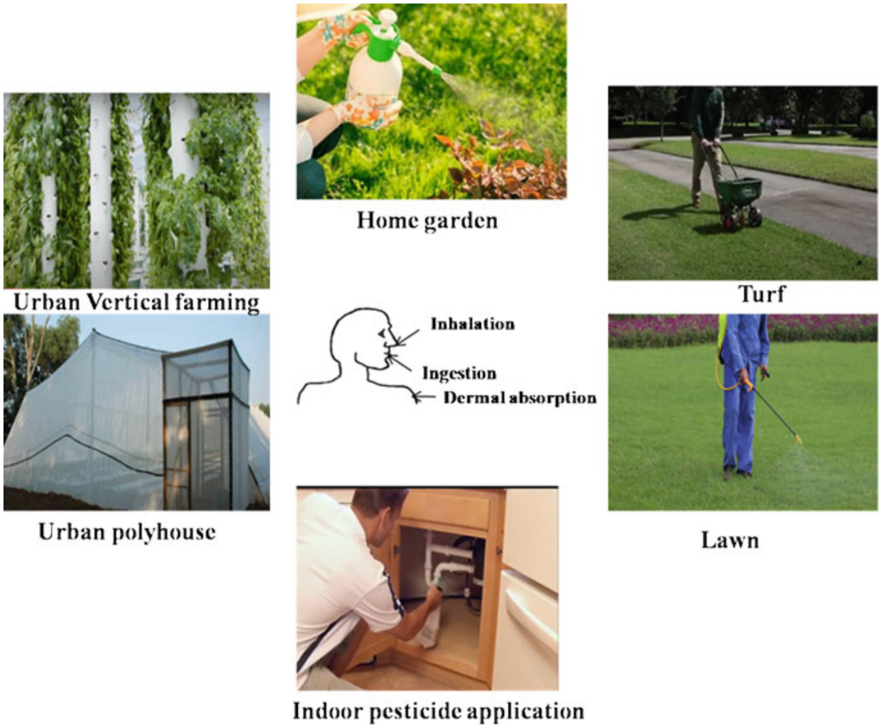

Fig. 41.4 Various ways of exposure of human and soil to pesticides in urban environment

level of OCPs was found in the roadside soil of Gwalior city, Madhya Pradesh (Kumar et al. 2018) and DDT and HCHs concentration ranged from <0.01–2.54 μg/kg and 1.3–27 μg/kg, respectively. The isomeric ratio indicates the combined use of lindane and technical HCH. Source identification also indicates the recent input of DDT along with aged residues to some aspect of long-range atmospheric transport. In another study, Kata et al. (2015) frequently detected δ-HCH, p,p'-DDE, endrin ketone and endosulfan sulphate in the urban soils of Hyderabad city (South India) and source identification indicates the present use of DDT and lindane. For HCH (0.9–20 μg/kg) and DDT (2–315 μg/kg), however, the values were lower than sediment quality guidelines indicating low health risk. Table 41.3 presents the DDT and HCH contamination level in the urban soils of India and the world.

Urban soils from central India, i.e. Korba, Chhattisgarh were found to contain 0.9–20 and 2–315 ng/g residues of ∑HCH and ∑DDT, respectively (Kumar et al. 2014b). α-HCH was the major HCH isomer with concentrations ranging from 0.9–9.3 ng/g and p,p′-DDE was the prime DDT isomer with 1.6–135 ng/g residue levels. The ratio of p,p′-DDT/p,p′-DDD+p,p′-DDE values was ranging from 0.1–2.6, which indicated the historical and fresh application of DDT. The ratio of o,p′-DDT/p,p′-DDT was ranging from 0.2–0.8, which indicated past and on-going applications of technical DDT, not dicofol. DDT (0.54–37.42 mg/kg) and HCH

Table 41.3 Level of ∑DDT and ∑HCH in urban soil of India and world

Location	Country	Land use	Year of sampling	∑DDT (μg/kg)	∑HCH (μg/kg)	References
Delhi	India	Urban	1974	10–2600	NA	Yadav et al. (1981)
Madras, Chidambaram, Trivandrum, Cochin, Panaji	India	Urban	1988	3.4–190	0.55–27	Kawano et al. (1992)
New Delhi, Agra, Kolkata, Mumbai, Goa, Chennai and Bangalore	India	Urban	2006–2007	2–410 ∑OCP		Chakraborty et al. (2015)
Delhi	India	Urban	2011	0.88–13.42	1.41–2.98	Kumar et al. (2014a)
Gwalior	India	Urban	2012	1.3–27.41	<0.01–3.54	Kumar et al. (2018)
Kurukshetra	India	Urban	2012	0.54–37.42	0.56–8.52	Kumar et al. (2013)
Korba	India	Urban	2012	2–315	0.9–20	Kumar et al. (2014b)
Beijing	China	Industrial	NA	3020–67,430	13,200–148,710	Wenrui et al. (2009)
Yinchuan	China	Urban	NA	0.577–1068	0.391–74.2	Wang et al. (2009)
Punjab	Pakistan	Urban	2011	8.6–210	1.7–20	Syed et al. (2013)
Novi Sad	Serbia	Urban	2014–2015	<LOD to 86.3	–	Škrbić et al. (2017)

(0.56–8.52 mg/kg) detected from the urban soil of Kurukshetra (Central India) were also below the guidelines value (Kumar et al. 2013). An extensive monitoring study was carried out by Chakraborty et al. (2015) covering an urban-suburban-rural tract of major cities of India situated in Northern (New Delhi and Agra), Eastern (Kolkata), Western (Mumbai and Goa) and Southern (Chennai and Bangalore) part of India. Region-specific usage of OCPs resulted in profound influences on regional variation rather than a local variation. Site-specific OCP deposition was found in New Delhi due to low winter temperature. Cities with higher ambient temperature resulted in HCH volatilization. They concluded that due to past and present uses of OCPs like DDT, it is expected that in the coming future there will be intermittent emission and re-emission of OCPs from Indian soil. In addition to urban soil, several studies have shown that peri-urban agriculture has resulted in a high concentration of trace metals and organic contaminants including pesticides in soil and environment (Chourasiya et al. 2015; Sharma et al. 2016; Chabukdhara et al. 2016).

41.4.4 Pesticides in Soil from Obsolete Pesticides Stores and Dumping Sites of India

Obsolete pesticides are those pesticides which are not used today due to severe restrictions or quality deterioration of active ingredient due to improper storage or prolonged storage beyond the date of expiry (Shetty et al. 2008). Due to prolonged storage they may produce metabolites which may be more toxic. Since they lost their usability, safe disposal of them is very much important considering their toxic properties. However, sometimes their safe disposal is costlier than their procurement cost which discourages the developing countries like India to adopt suitable remediation measures. On the other hand, reports are available which revealed that these obsolete pesticides stock contamination may travel to long range and may pollute the air, water and environment (Zhang et al. 2008; Dvorská et al. 2012).

One of the important OCPs, i.e. technical HCH (t-HCH) has caused several global concerns due to its indiscriminate disposal at dumpsites including India. HCH is synthesized through photochlorination of benzene which resulted in a mixture of different stereoisomers (α-, β-, γ-, δ-, ε-, η-, and ξ-HCH), known as technical HCH (t-HCH). However, among these only γ-HCH (lindane) has insecticidal properties which constitute only 8–15% of t-HCH. During purification of γ-HCH from t-HCH, a huge amount of waste of other isomers of HCH generated. An approximate estimation indicates that for 1 ton production of γ-HCH (lindane), almost 8–12 tons of HCH waste generated (Vijgen et al. 2006), known as "muck HCHs" which are either stocked in the industrial unit or discarded in the dumpsites (Willet et al. 1998; Vijgen et al. 2011, 2019). Globally, almost 4–7 million tons of "muck HCHs" is present in different dumpsites (Willet et al. 1998; Vijgen et al. 2011). A stockpile of HCH has been discovered in various countries like Spain (Navarro et al. 2019), Germany (Kalbitz and Popp 1999), Pakistan (Alamdar et al. 2014) and Brazil (Österreicher-Cunha et al. 2003). Though HCH is banned in India, lindane is still used for vector control activities which leads to severe environmental concern in surrounding areas of production and dumping sites (Abhilash and Singh 2008; Jit et al. 2011).

Various reports are available for locally HCH contaminated hotspot near to the surrounding areas of lindane manufacturing unit. An alarming level of presence of HCH isomers (α-HCH: 38.1–98 mg/kg; β-HCH: 75–463; γ-HCH: 3.5–7.0 mg/kg; δ-HCH: 3.7–11 mg/kg) was reported from the soil samples obtained from the dumpsite and the surrounding area of India Pesticides Limited (IPL), a lindane manufacturing unit, Lucknow, India (Prakash et al. 2004). Abhilash and Singh (2008) screened the soil samples surrounding the lindane production unit, Lucknow and detected a high level of t-HCH (53–99 mg/kg) which indicates an immediate measure has to be taken for soil remediation. Widespread HCH contamination has also been reported by Jit et al. (2011) at the lindane production site, Uttar Pradesh and the surrounding area of this unit and HCH dumpsites. Very high level of ∑HCH (450 g/kg) was detected in dumpsites which indicates that no remediation measures were taken to cover up this contamination. High level of HCH was also detected in the nearby agricultural field and river water (Reetha and Sharda river) which may be due to wind-drift and run-off from the dumpsite. Dadhwal et al. (2009) also reported a high level of ∑HCH (4–125,280 μg/g soil) from HCH manufacturing industrial unit, North India and its dumpsite and surrounding area. Groundwater (Handpump: 2.3 μg/ml) and agricultural soil (6–1854 μg/g) located near to dumpsite and surface water (small drain: 2.1 μg/ml) near to manufacturing unit also contain a very high level of HCH. Though there are many dumpsites for obsolete pesticides particularly HCH dumpsites are detected but hardly any effective remediation measures are taken since neither public nor the government is well versed with this problem and consequently this may be brought disaster in terms of environmental pollution in any time.

Other than obsolete pesticide dumpsites, pesticides was also found in the solid waste dumping sites. Urban and house garden agriculture, contaminated agricultural and home waste, packing materials, pesticides spray for city vector control programs, use of pesticides in dumping site for public hygiene are the main source of pesticide pollution in solid waste dumping sites (Minh et al. 2006; Sultan et al. 2019). However, in India, limited information is available about the pesticide level in solid waste dumping sites.

Minh et al. (2006) screened the soil collected from dumping sites of different Asian countries including India (Chennai) and results showed elevated levels of HCH in India as compared to other Asian countries. In general DDT and HCH contamination was thousand times higher than the general soil implying human health risk particularly to the rag pickers and children who collected recyclable materials from the dumping ground. Gupta et al. (2013) also detected a high level of OCPs in the solid waste dumping sites of Agra, India. The level of ∑HCH, ∑DDT, endosulfan, dieldrin, aldrin, heptachlor was in the range of 0.55–1.62, 0.49–1.82, 0.08–0.23, 0.05–0.92, 0.92–2.3, 0.24–0.53 mg/kg, respectively. This high content of pesticides in the dumping sites may increase the dis-equilibrium of pesticides in the air–soil interface which may favour for their emission from the soil and their long-range transport particularly for HCH and it is necessary to study their potentially harmful impact on human health and environment.

41.4.5 The Occurrence of Pesticide Pollution in Sediment from India and Associated Risk Assessment to Aquatic Ecosystems

Sediments are the major sink of pesticides in the environment and can also act as a source where pesticides may release to the environment again. Pesticides can enter into the sediment by various means like run-off, discharge, direct dumping, wet or dry deposition along with many other processes (Yang et al. 2005). Polluted sediment ultimately may contaminate the potable water, fish and agricultural commodities and finally, the human being through ingestion of polluted food and water (Zhou et al. 2006). Along with the current contamination level, historical inputs of pesticides in the aquatic body can also be determined by analysis of the sediment core (Hendy and Peake 1996). Sometimes the level of contamination in sediment may be higher than the water and under the favourable condition, it may release the pesticides into the water and thus affecting the aquatic fauna including fish. Pesticide pollution in sediment may also affect the sediment-dwelling organisms and benthic community and thus may affect the overall sediment health.

Documentation on the occurrence of pesticide content in the sediment environment of India was started in the 1970s and 1980s covering different type of water bodies including rivers [Ganga (Senthilkumar et al. 1999), Yamuna (Agarwal et al. 1986; Parween et al. 2014;Verghese 2015), Gomti (Malik et al. 2009), Brahmaputra (Mishra et al. 2013), Hooghly (Mondal et al. 2018; Khuman et al. 2020a, b), Tapi (Hashmi et al. 2020), Sabarmati (Hashmi and Menon 2015), Cauveri (Rajendran and Subramanian 1999), Vellar river (Ramesh et al. 1991), and Thamirabarani (Kumarasamy et al. 2012)], lakes, reservoirs, wetland [Chilika (Nag et al. 2020), East Kolkata Wetland (Nag et al. 2016), Kolleru lake (Sreenivasa Rao and Pillala 2001), Ramgarh water reservoir (Gupta et al. 2016), Tighra reservoir (Rao and Wani 2015)], marine (Kureishy et al. 1978; Tanabe and Tatsukawa 1980; Sarkar and Sen Gupta 1987, 1988a, b, 1989, 1991; Rajendran et al. 2005; Sarkar et al. 1997; Pandit et al. 2006; Sarkar et al. 2008; Singare 2015; Khuman et al. 2020a, b) as well as estuarine [Cochin Estuary (Akhil and Sujatha 2014), Hooghly river estuary (Guzzella et al. 2005; Mitra et al. 2019), and Vembanad Estuarine, Kerala (Sruthi et al. 2018] sediment and some reports indicate that the level of pesticide contamination is of grave concern.

However, most of the studies are concentrated on hydrophobic pesticides like OCPs as they can easily be sorbed by the suspended particulate matters. As shown in Tables 41.4, 41.5, and 41.6, initially most of the sediments of the river, lake, estuarine and marine water bodies of India were screened for HCH, DDT and their metabolites (Kureishy et al. 1978; Tanabe and Tatsukawa 1980; Agarwal et al. 1986; Sarkar and Sen Gupta 1988a; Ramesh et al. 1991; Rajendran and Subramanian 1999; Sarkar et al. 1997; Rajendran et al. 2005; Guzzella et al. 2005; Pandit et al. 2006; Mishra et al. 2013; Sarkar et al. 2008; Mitra et al. 2019). Over time other OCPs like endosulfan, aldrin, chlordane, heptachlor and methoxychlor were also included (Sarkar and Sen Gupta 1987, 1988b, 1989, 1991; Senthilkumar et al. 1999; Malik et al. 2009; Kumarasamy et al. 2012; Parween et al. 2014; Akhil and Sujatha 2014; Hashmi and Menon 2015; Sruthi et al. 2018; Khuman et al. 2020a, b). Few studies also included OPs and SP (Sreenivasa Rao and Pillala 2001; Singare 2015; Nag et al. 2016, 2020; Hashmi et al. 2020). Very few studies also included herbicides and fungicides (Mondal et al. 2018) along with OCPs. New-generation pesticides like fipronil was also included for screening the river sediment (Kaur et al. 2019). However, the level of contamination in the sediment of different water bodies is not straightforward and it varies depending upon the type of water bodies, sampling time and the condition.

Among the freshwater aquatic bodies, for assessment of pesticides, river sediments are thoroughly studied and it can act as a temporary or permanent repository of pesticides input through point or non-point sources (Chakraborty et al. 2019). Though Ganga river is an important riverine system of India, limited studies were carried out related to the sediment pesticide pollution (Senthilkumar et al. 1999). However several studies have been carried out in the sediment of

Table 41.4 Detected pesticide residues (ng/g) in the sediment of freshwater resources in India

Sampling location (year of sampling)	∑DDT	∑HCH	∑Heptachlor	Aldrin	Dieldrin	∑Endosulfan	Chlorpyrifos	Ethion	Malathion	Methyl Parathion	References
Vellar river, Tamil Nadu (1988–1989)	0.78–8.6	1.9–27	–	–	–	–	–	–	–	–	Ramesh et al. (1991)
Tamiraparani river, South India (2008–2009)	<0.01–857	<0.01–472	–	<0.02–562	<0.03–1693	–	–	–	–	–	Kumarasamy et al. (2012)
Brahmaputra river, Dibrugarh, Assam (2009–2011)	69.1–852	71.2–655	–	–	–	–	–	–	–	–	Mishra et al. (2013)
Brahmaputra river, Nagaon, Assam (2009–2011)	72.5–633	39.2–728	–	–	–	–	–	–	–	–	Mishra et al. (2013)
Yamuna river, Delhi (2010)	12.38	40.32	0.46	0.82	–	–	–	–	–	–	Parween et al. (2014)
Sabarmati river, Gujarat (2013)	BDL-34.71	BDL-1494.62	–	–	–	BDL-21.21	–	–	–	–	Hashmi and Menon (2015)
Yamuna river, Agra (NA)		274–405	–	–	–	–	–	–	–	–	Verghese (2015)
Deomoni river, West Bengal (2013–2015)	–	–	–	–	–	–	51.3 ± 8.5	127.1 ± 12.2	–	–	Singh et al. (2015a, 2015b)
Hooghly river, West Bengal (2014–2016)	0–1.400	0–2.216	–	–	–	0–0.270	BDL	–	–	BDL	Mondal et al. (2018)
Tapi river, Gujarat (2013–2014)	0.52–0.72	BDL	–	–	–	38.38	BDL	–	–	0.77	Hashmi et al. (2020)

Pichavaram mangrove, Tamil Nadu (1988–1999)	0.25–2.0	0.9–17	–	–	–	–	–	–	–	–	Ramesh et al. (1991)
Pond, Dibrugarh, Assam (2009–2011)	30.1–928	72–834	–	–	–	–	–	–	–	–	Mishra et al. (2013)
Pond, Nagaon, Assam (2009–2011)	154–932	142–743	–	–	–	–	–	–	–	–	Mishra et al. (2013)
Kolleru Lake, Andhra Pradesh (NA)	BDL-191	2.6–600	–	–	BDL-128	–	1.1–292	–	–	–	Sreenivasa Rao and Pillala (2001)
Ramgarh water reservoir, Rajasthan (1996–1997)	2700	100–8500	BDL-770	–	–	–	–	–	–	–	Gupta et al. (2016)
East Kolkata Wetland, Kolkata (2012)	7.39–8.31 (7.85 ± 0.46)	BDL	–	–	–	5.26–11.11 (7.67 ± 2.49)	–	–	–	–	Nag et al. (2016)
Chilika Lake, Odisha (2012–2016)	Among the OCPs, OPs, and SPs, only fenpropathrin (SP) was detected at a concentration of 81 ng/g										Nag et al. (2020)

NA not available, *BDL* below the detection limit

Table 41.5 Pesticides (ng/g) in the marine sediments from various regions of India

Sampling location (year of sampling)	∑DDT	∑HCH	∑Heptachlor	Aldrin	Dieldrin	∑Endosulfan	Chlorpyrifos	Ethion	Malathion	Methyl parathion	References
Bay of Bengal, East coast of India (NA)	20–490	–	–	–	–	–	–	–	–	–	Sarkar and Sen Gupta (1988a)
Bay of Bengal, Tamil Nadu and Pondicherry (1998)	0.04–4.79	0.17–1.56	–	–	–	–	–	–	–	–	Rajendran et al. (2005)
Bay of Bengal, East Coast of India (1984–1985)	20–780	10–210	–	20–530	50–510	–	–	–	–	–	Sarkar and Sen Gupta (1988b)
Coastline of Mumbai, Maharashtra (NA)	0.5–9.6	3.8–16.2	–	–	–	–	–	–	–	–	Pandit et al. (2006)
Vasai estuarine Creek, Mumbai, Maharashtra (2009–2011)	173–558	5–68	–	57–164 (122.04)	61–187 (124.69)	123–498 (317.71)	192–570 (396.79)	275–532 (401.35)	–	–	Singare (2015)
Coastal sediment, South-west coast, India (2015)	BDL-141	BDL-111	–	BDL-108	BDL-49	BDL-17	–	–	–	–	Khuman et al. (2020b)

Backwater sediment, South-west coast, India (2015)	BDL-9 (3 ± 3)	11–35 (25 ± 8)	BDL-197 (33)	3–20 (11 ± 7)	3–19 (9 ± 5)	BDL-7 (1 ± 2)	–	–	–	–	Khuman et al. (2020b)
Estuarine sediments of Arabian Sea, West coast of India (NA)	1.47–25.17	0.85–7.87	–	0.10–0.26	0.70–3.33	–	–	–	–	–	Sarkar et al. (1997)
Offshore sediments of Arabian Sea, West coast of India (NA)	1.14–17.59	0.10–6.20	–	0.09–0.26	0.20–1.41	–	–	–	–	–	Sarkar et al. (1997)
Arabian Sea (1985–1990)	7.4–179.1	BDL-17.9	–	0.9–35.7	BDL–0.88	–	–	–	–	–	Shailaja and Sarkar (1992)
Bay of Bengal (1985–1990)	0.02–720	0.01–0.21	–	0.01–0.05	0–0.5	–	–	–	–	–	Shailaja and Sarkar (1992)

NA not available, *BDL* below the detection limit

Table 41.6 Pesticides (ng/g) contamination in the estuarine sediments of India

Sampling location (year of sampling)	∑DDT	∑HCH	∑Heptachlor	Aldrin	Dieldrin	∑Endosulfan	Chlorpyrifos	Ethion	Malathion	Methyl Parathion	References
Cochin Estuary, Kerala (2009–2011)	229–418	23.7–423	BDL-69.4	BDL-33.2	BDL-142.4	BDL-350.5	–	–	–	–	Akhil and Sujatha (2014)
Hooghly river estuary, East India (NA)	0.14–18.6	0.10–0.6	–	–	–	–	–	–	–	–	Mitra et al. (2019)
Lower stretch of Hugli estuary, West Bengal (2003)	0.18–1.93	0.11–0.40	–	–	BDL	–	–	–	–	–	Guzzella et al. (2005)
Sundarban Wetland, Northeastern Part of Bay of Bengal, (2005)	0.05–11.5	0.05–12	–	–	–	–	–	–	–	–	Sarkar et al. (2008)
Vembanad Estuary, Kerala (NA)	2.5–30.50	1.2–32.13	1.9–8.5	0.1–59.90	–	2.19–143.26	–	–	–	–	Sruthi et al. (2018)

NA not available, *BDL* below the detection limit distributaries and tributaries of Ganga river [Yamuna (Agarwal et al. 1986; Parween et al. 2014; Verghese 2015], Gomti (Malik et al. 2009) and Hooghly (Mondal et al. 2018; Khuman et al. 2020a, b]. Senthilkumar et al. (1999) detected average concentration of HCH and DDT from the sediment of Ganga river at a level of 2.6 ng/g and 5.6 ng/g, respectively. Malik et al. (2009) assessed the OCP contamination in Gomti river sediment. ∑OCP residues in the sediment ranged from 0.92–813.59 ng/g. The isomeric ratio suggests the on-going use of DDT and lindane along with the past usage. Aldrin was frequently detected due to its high persistence. A lower level of endosulfan and high level of its metabolites, i.e. endosulfan sulphate indicate the long-time use of this pesticide. Parween et al. (2014) reported the mean ∑OCPs content in the Yamuna river sediment was 61.6 ± 23.6 ng/g and the values were different from the other previous studies (Pandey et al. 2011; Kumar et al. 2012) carried out in the same area. The isomeric ratio of HCH indicates that both lindane and technical HCHs were used recently. The study also indicates the present usage of DDT and aldrin. However, the level of heptachlor and endosulfan and their metabolites indicates the historical usage.

The sediment of the Hooghly river, a tributary of Ganga was also screened for pesticides (Mondal et al. 2018; Khuman et al. 2020a, b). Khuman et al. (2020a, b) screened the Hooghly river sediment across the urban and suburban transect and reported average concentration of 10, 5 and 4 ng/g for DDT, HCH and endosulfans, respectively. The values were high as compared to previous reports for the same area (Guzzella et al. 2005), indicating their on-going uses. The dominance of DDT in river sediment indicates its present use in vector control programs. Due to closeness to the agricultural areas, suburban transects showed higher values for OCPs as compared to urban transect and source identification indicates the recent use of DDT, lindane and endosulfan. Along with OCPs, Mondal et al. (2018) also assessed the OPs, herbicides and fungicides in Hooghly river sediment. However, except OCPs, none of the other pesticides was detected and the sources are supposed to be the old sources for HCH and fresh use of DDTs. An alarming level of DDT (average 287–330 ng/g) and HCH (average 321–378 ng/g) was detected in the sediment of pond and Brahmaputra river system from North-East India and the values were highest amongst the previous reports (Mishra et al. 2013). A high level may be associated with their extensive use in both agricultural and public health sector due to their low cost and higher efficiency (Mishra and Sharma 2011). Source identification indicates the past and present use of technical DDT, technical HCH and lindane.

In general, the rain-fed river of South Indian states showed a low level of OCP contamination than the snow-fed river of North Indian state. However, higher loads for DDT and HCH were reported by Ramesh et al. (1991) for Vellar river. Rajendran and Subramanian (1999) reported a higher concentration of HCH (4.35–158.4 ng/g) in the Cauvery river sediment of the south-eastern coast of India which indicates the extensive use of it in agricultural activities. Low concentration and not wide variations for DDT content in the Cauvery river sediment indicates its ban in agriculture and used for vector control. Kumarasamy et al. (2012) assessed 17 OCPs in the sediment of the south Indian river Thamiraparani, which shows the heterogenic nature of the non-point source of pollution. Agricultural and municipal discharge resulted in high pesticide concentration in upper and lower stretches, whereas frequent damming in middle stretches reduces the pesticide contamination. A higher value was found for ∑DDT than ∑HCH and this was following the fact that as compared to HCH, DDT was used more in this river basin. Source identification indicates the previous and recent usage of DDT for agricultural activities. The sediment of western Indian rivers was also screened for pesticides (Hashmi and Menon 2015; Hashmi et al. 2020). Hashmi et al. (2020) detected endosulfan (38.4 ng/g), DDT (0.65 ng/g) and methyl parathion (0.65 ng/g) in the sediment of Tapti river, Gujarat. A higher level of pesticides in sediment than water indicates that pesticides were not used recently.

Compared to freshwater sediment, marine and estuarine sediments are more exhaustively studied in India. Accumulation of pesticides in marine sediment may be due to river discharge or discharge from agricultural/industrial sources. Pesticide level in the ocean is of more concern since the persistence of pesticides appears to be more and in some semi-enclosed areas of seas, the removal rate of pesticides is very slow (Wu et al. 1999). Pesticide contamination, more particularly OCPs pollution in marine sediment has been well documented in the long back (Kureishy et al. 1978; Tanabe and Tatsukawa 1980; Sarkar and Sen Gupta 1987; Pandit et al. 2002) signifying the occurrence of their potential emission sources.

A high concentration (ng/g) of ∑DDTs (20–780), HCH (10–210), aldrin (20–530) and dieldrin (50–510) was detected in the sediment of Bay of Bengal (Sarkar and Sen Gupta 1988b). A large influx of contaminated river water to the ocean might have contributed to this high level of contamination. HCH (0.44–17.9 ng/g) was the most frequently detected pesticide in the sediment of Arabian Sea, West-central coast of India (Sarkar and Sen Gupta 1987). However, another study by Sarkar and Sen Gupta (1991) observed a high level of ∑DDT contamination in the sediment of Arabian sea, West Central coast and aldrin dominated over dieldrin and amongst the HCH isomers, γ-HCH was pre-dominant. Pandit et al. (2006) studied the marine sediment of Mumbai, Maharashtra for OCP contamination. The highest concentration was for ∑HCH (3.8–16.2 ng/g) and results indicate the usage of lindane formulation. Shailaja and Sarkar (1992) detected a higher level of pesticides, more particularly ∑DDT in the sediment of Bay of Bengal as compared to the Arabian Sea. This was attributed to the fact that suspended sediment load from the river to sea was very high in the Bay of Bengal as compared to the Arabian Sea. Recently, Khuman et al. (2020a, b) reported frequent detection of OCPs like HCH, dieldrin, endrin and its metabolites in the coastal and backwater transect of the south-west coast, India. Source identification indicates the present use of DDT and the past use history for endosulfan. However, the values were lower than the soil contamination from Cochin and Thiruvananthapuram (Kawano et al. 1992).

Various studies documented the pesticide contamination in estuarine sediment. Since estuaries are the interface between lands and sea, estuarine inputs are important in terms of pesticide pollution. Pesticides applied in lands through run-off and leaching may ultimately get accumulated into the bottom of the estuary. Frequently studied estuarine system in India is the Hooghly estuary and Sundarban wetland system, Eastern coastal part of India. Guzzella et al. (2005) observed a wide fluctuation in mean contamination and spatial differences for DDT (0.18–1.9 ng/g), HCH (0.11–0.4 ng/g) and HCB (0.5–0.98 ng/g) in the sediment of Hooghly estuary and Sundarban wetland of eastern coast of India. The isomeric ratio of HCH and DDT indicates the use of them both for agricultural and vector control activities. Heterogenic distribution of HCH isomers indicates the isomerization of some of the HCH isomers during the process of transport and transformation in a marine environment. A complete investigation was carried out by Sarkar et al. (2008) to screen Sundarban wetland sediment, East India for OCPs contamination. The reported pooled mean concentration (ng/g) was in the following range-∑DDTs, from 0.5–11.47, ∑HCH from 0.05–12.4 and HCB, from 0.05–1.39. This indicates irregular pesticide distribution attributing to the hydrological features of Sundarban wetland reflecting non-homogenous inputs. In recent years several studies (Mitra et al. 2019; Zanardi-Lamardo et al. 2019) have been carried out to determine the organic pollutants including OCPs in the Hooghly estuary sediment. A study carried out by Mitra et al. (2019) for Hooghly estuary indicates the wide variation for concentration (ng/g) of ∑DDT (0.14–18.6) and ∑HCH (0.1–0.6). Source identification for DDT indicates the inputs of weathered DDT and their degradation along with industrial input due to on-going use of DDT as an antifouling agent to maintain the boat (Yu et al. 2011). In contrast to the previous study (Guzzella et al. 2005), where α-HCH was dominated in Hooghly estuary, a recent study by Mitra et al. (2019) for this estuary indicates the dominance of γ-isomer, which reflects the successful implementing of banning of HCH by Govt. of India and encouragement for use of lindane (99% pure γ-isomer) for vector control. Zanardi-Lamardo et al. (2019) only detected ∑DDT (not detected to 8.97 ng/g) in the sediment of Hooghly estuary and Sundarban mangrove and this trend was consistent with Sarkar et al. (2008) for the same area. Prevalent of p,p′-DDT indicates the past and present use of this pesticide.

Few studies are also available for estuarine systems in South India. Sruthi et al. (2018) assessed the OCPs and metal content in the Vembanad estuarine system, Kerala. Almost all the studied OCPs were detected in the sediment system. Level of endosulfan residues, presence of endrin ketone (a metabolite of endrin), aldrin and dieldrin and results of isomeric ratio of HCH and DDT indicate the recent incursion of these pesticides into the Vembanad estuary system. Whereas, the results of the ratio of DDT metabolite analysis in Cochin Estuary, Kerala as studied by Akhil and Sujatha (2014) indicate the accumulation of aged and weathered residues. The concentration of DDT and HCH in Cochin and Vembanad estuary system was higher than the reported value for Hooghly estuary and Sundarban wetland. Along with tourism activities, port development activities, use of cocktails of OCPs in agricultural sector, fertilizer and oil refinery plant, municipal discharge altogether have contributed to this higher values of detected pesticides in Cochin and Vembanad estuary. In western India, Singare (2015) assessed the pesticide pollution in the sediment of Vasai creek, an estuarine creek situated near to Mumbai, Maharashtra. Source identification indicates the present use of DDT and lindane as this Creek is situated near the highly urbanized city Mumbai and these OCPs may be used continuously for city malaria control programme. Sarkar et al. (1997) detected a higher level of ∑DDT and dieldrin in the estuarine sediment of Arabian seas as compared to offshore sediment and ∑HCH, aldrin and endrin contamination level was similar for both the system. Zuari and Kali estuary was the most susceptible system with reference to DDT contamination.

There are several factors which regulate the contamination level of pesticides in the sediment of both freshwater and marine environment. Physicochemical properties of both sediment (pH, organic matter content, texture and clay mineral composition, elemental composition, etc.) (Sarkar and Banerjee 1987; Sarkar 1994) and pesticides (partition coefficient, vapour pressure and degradation capacity) influence the occurrence and level of contamination. The texture of sediment plays an important role as a pesticide retaining capacity of clay-sediment is higher than sandy or silty sediment (Sarkar 1994). Sediment organic carbon also plays an important role. In general, a strong correlation between sediment organic carbon and pesticide level indicates the past usage of pesticide, whereas no-correlation indicates recent pesticide usage (Chakraborty et al. 2015; Khuman et al. 2020a, b). However, this fact is not necessarily true always. Rate of discharge of contaminated waste along with hydrological characteristics, construction of dam particularly in river basin may also influence the spatio-temporal variation in the pesticide content in sediment (Kumarasamy et al. 2012).

The season has also a profound influence on the content of pesticides in sediment. The mean concentrations of ∑OCPs were highest in Yamuna river sediment during monsoon season (Parween et al. 2014). This coincides with the application of pesticides before the onset of monsoon to control mosquitoes as monsoon is the ideal time for their breeding. Malik et al. (2009) also found a similar observation in Gomti river sediment. Besides, the composition of individual pesticides also varied with the season. High temperature in summer resulted in high volatilization and degradation of pesticide which lead to a higher concentration of metabolites as compared to the parent metabolites. Due to low solubility, the concentration of DDT was found to be lower in the monsoon season. Mondal et al. (2018) found a large number of pesticides at low concentration in the sediment of Hooghly river during monsoon season. This attributes to the large influx of agricultural run-off and from point sources from different places along with dilution effect. However, the concentration of pesticides was much higher during pre- and post-monsoon attributing to the water volume reduction. Strong monsoonal current led to the removal of topsoil with the fine-grained portion of the sediment, which resulted in low concentration of pesticides in the sediment of Vasai creek Mumbai during monsoon season (Singare 2015).

To determine the impacts of sediment pesticides on human and aquatic health, various sediment quality guidelines (SQG) have been developed by different agencies for both freshwater and marine sediment (MacDonald et al. 1996; NOAA 1999; CCME 2002; Wisconsin Department of Natural Resources 2003) and each approach has its own advantages and disadvantages (MacDonald et al. 2000). These guidelines values can be used in evaluating human and ecological risk linked to sediment pesticide pollution, also for designing the monitoring programs, determination of historical pesticide contamination, and ultimately for effecting planning to implement the remediation measures (Birch 2018). SQG also allows us to determine how sediment toxicity can affect the organism or their community at various stages of the life cycle (McCauley et al. 2000).

In India, no environmental guidelines have been established for the sediment pesticide contamination. Among the different SQGs defined by international agencies, effect range low (ERL)/effect range medium (ERM) and threshold effect level (TEL)/probable effect level (PEL) are the most widely used for determining the risk associated with individual pesticides in sediment. As developed by Long et al. (1995), ERL is the particular value above whose adverse effect on sensitive aquatic species may begin to be observed, whereas ERM value represents the mass fraction below whose adverse effects are expected to occur only rarely. As provided by Macdonald et al. (1996), TEL represents the concentration below whose adverse effects are expected to occur rarely, whereas PEL is the concentration above whose chances of adverse biological effect are frequent. However, there are always possibilities of multiple contaminations in sediment and accordingly Long and MacDonald (1998) have proposed mean effects range median quotient (M-ERM-Q) for evaluating the combined effect of multiple pesticides which exceeds the ERM/PEL.

Akhil and Sujatha (2014) observed that almost all the pesticides detected in Cochin estuary exceed the SQG. Ecotoxicological study for pesticides in the sediment of Vasai creek, Mumbai indicates that o,p′-and p,p′-DDT and total DDT concentration exceed the TEL, PEL, ERL and ERM values (Singare 2015). For Hooghly river sediment, Khuman et al. (2020a, b) reported that risk by TEL for γ-HCH and p,p′-DDT was higher than the risk indicated by PEL. Most of the sites of Gomti river sediment cross the lindane level above TEL as observed by Malik et al. (2009) which may contribute the toxicity to the freshwater ecosystem. Parween et al. (2014) also reported that γ-HCH, p,p′-DDT and total DDT level of Yamuna river sediment were above TEC and PEC. Kumar et al. (2012) also reported that 47.6% of sediment sample of Yamuna river contaminated with γ-HCH above the PEL. Sarkar et al. (2008) found intermediate sediment toxicity for ∑DDT in Sundarban wetland sediment as the values cross ERL but below the ERM. However, the level of γ-HCH poses risk for marine inhabitants as 40.5% of sediment sample crosses PEL value. Based on SQG, Rajendran et al. (2005) reported some of the sediment samples of Bay of Bengal can be categorized as polluted concerning DDT and γ-HCH.

41.5 Pesticide in Soil and Associated Human Health Risk Assessment

To continuously feed a nation of 1.3 billion population, application of pesticides in Indian agricultural system, staring from soil preparation to harvesting and post-harvesting operations till reaching every Indian, is indispensable. The Indian agricultural system is facing challenges of cropping area shrinkage, lowering of natural resources coupled with labour migration, which has forced farmers to grow more from fewer resources. Hence, to prevent crop losses due to pest attacks, farmers have been found to apply pesticides more frequently than the recommended doses (Shetty 2004). The external pressure of pesticides on pests has resulted in the development of resistance and resurgences in pests, and the outcome is increasing nuisance from pests. Hence, farmers are applying pesticides more frequently without knowing the hidden damages to the environment. In India, still generic pesticides share the major portion of the pesticide market. Though several OCPs have been either banned or restricted for application in agriculture, illegal applications of restricted/banned pesticides (like DDT, HCH) and use of misbranded and substandard pesticides have resulted in accumulation of pesticides, mainly OCPs like DDT, HCH, endosulfan, aldrin, chlordane, dieldrin, etc. in all environmental components including soil. These OCPs are toxic, lipophilic, bioaccumulative, carcinogenic, a threat to various organisms (ATSDR 2005, 2008) and can move from one place to another by atmospheric transfer (Pozo et al. 2011). It can be seen from Table 41.2 that DDT and HCH residues were the commonly encountered pesticide residues across various states of India over the past 30 years. Not only in India, but DDT and HCH are also at the centre of global concern as addressed by the European Union (EC 2001), United States Environmental Protection Agency (USEPA 2015a), Stockholm Convention on POPs (Persistent organic pollutants) (SC (Stockholm Convention) 2015, etc. Environmental guidelines for residues of DDT, HCH, etc. have not been established in India. Hence, in many case studies, researchers have followed the guideline framed by the Canada government, National Oceanography and Atmospheric Administration (NOAA), the USA or the Chinese guidelines. 700 ng/g is the limit for total DDT in agricultural soils as set by the Canada government (CCME 2007), whereas the limit for total HCH in agricultural soil is 20 ng/g soil, which has been defined by NOAA (Buckman 1999). Further, China has proposed a guideline after considering both DDT and HCH in agricultural soils as: low pollution (<50 ng/g), light pollution (50–500 ng/g), moderate pollution (500–1000 ng/g) and heavy pollution (>1000 ng/g) (Wang et al. 2008). As seen from Table 41.2, in most of the Indian soil, DDT and HCH pollutions were much below the prescribed guidelines, however, specifically Nagaon and Dibrugarh districts of Assam showed moderate pollution levels. Therefore, pesticide-contaminated soils can play as the main pathway to contaminate human beings. By considering the toxicological importance of DDT and HCH, human health risk assessments have been reported by some researchers in terms of lifetime average daily dose (LADD), non-cancer risk as hazard quotient (HQ) and incremental lifetime cancer risk (ILCR) as per recommended guidelines of USEPA (1989) and Environment Agency (EA) (2009). LADD, HQ and ILCR were calculated as:

$$\mathrm{LADD\ (mg/kg/day)} = (\mathrm{Cs} \times \mathrm{IR} \times \mathrm{F} \times \mathrm{EF} \times \mathrm{ED})/(\mathrm{BW} \times \mathrm{AT})$$

$$\mathrm{HQ} = \mathrm{LADD}/\mathrm{RfD}$$

$$\mathrm{ILCR} = \mathrm{LADD} \times \mathrm{CSF}$$

Table 41.7 LADD values of some pesticides in various soils of India

Place	Pesticides	Adult (mg/kg/day)	Children (mg/kg/day)	References
Southern India				
Idukki, Kerala	∑DDT	3.1×10^{-14} to 1.24×10^{-7}	4×10^{-14} to 1.61×10^{-7}	Joseph et al. (2020)
	∑endosulfan	1.01×10^{-12} to 1.42×10^{-7}	1.307×10^{-12} to 1.84×10^{-7}	
	Endrin	5.5×10^{-14} to 1.01×10^{-7}	7.1×10^{-14} to 1.31×10^{-7}	
	Dieldrin	5×10^{-15} to 5.034×10^{-8}	6×10^{-15} to 6.526×10^{-8}	
Central India				
Gwalior, Madhya Pradesh	∑HCH	1.4×10^{-9} to 5.9×10^{-9}	4.8×10^{-9} to 2×10^{-8}	Kumar et al. (2018)
	∑DDT	2.2×10^{-9} to 4.6×10^{-8}	7.4×10^{-9} to 1.6×10^{-7}	
Korba, Chhattisgarh	α-HCH	1.0×10^{-9} to 1.3×10^{-8}	6.4×10^{-9} to 6.9×10^{-8}	Kumar et al. (2014a, 2014b)
	γ-HCH	1.2×10^{-9} to 1.5×10^{-8}	6.6×10^{-9} to 7.5×10^{-8}	
	op-DDT	1.7×10^{-9} to 5.1×10^{-8}	8.7×10^{-9} to 2.7×10^{-7}	
	pp-DDT	1.0×10^{-9} to 1.7×10^{-7}	6×10^{-9} to 8.6×10^{-7}	

where Cs shows the individual pollutant′s concentration in the soil (mg/kg), IR indicated the ingestion rate of soil (100 and 200 mg/day for adult and children, respectively), F represents unit conversion factor (10^{-6}), EF denotes exposure frequency (365 days/year), ED denotes the lifetime exposure duration (12 and 70 years for children and adult, respectively), BW denotes the body weight (27 and 60 kg children and adult, respectively), AT (days) signifies the averaging time for carcinogens (EF x ED). CSF and RfD correspond to the cancer oral slope factor and reference dose, respectively, for individual compound (mg/kg/day) (USEPA 2015b). The contaminant's concentration becomes harmful when LADD > RfD. For regulatory purposes, ICLR and HQ are most frequently used to understand the health risk. ICLR value less than 10^{-6} indicates safety, whereas an ICLR value between 10^{-6} to 10^{-4} indicates low risk and a value more than 10^{-4} indicates the high risk from the contaminant. A HQ value ≥1 indicates a high risk associated with the contaminant. The LADD, ICLR and HQ values of some of the commonly detected OCPs from various agricultural soils of India have been presented in Tables 41.7, 41.8, and 41.9, respectively. It can be understood from the data that contamination of agricultural soils with OCPs is a serious issue, but human health risk due to these pesticides through soil exposure is very low as ICLR values are mostly below 10^{-6} and HQ values were far less than 1. Hence, necessary steps must be initiated to reduce the pesticide load of agricultural soils for a sustainable environment.

Table 41.8 ICLR values of some pesticides in various soils of India

Place	Pesticide	Adult (mg/kg/day)	Children (mg/kg/day)	References
Southern India				
Idukki, Kerala	∑DDT	1.061×10^{-14} to 4.237×10^{-8}	1.38×10^{-14} to 5.49×10^{-8}	Joseph et al. (2020)
	Dieldrin	7.324×10^{-14} to 8.05×10^{-7}	9.495×10^{-4} to 1.044×10^{-6}	
	γ-HCH	9.52×10^{-15} to 6.42×10^{-8}	1.23×10^{-14} to 8.32×10^{-8}	
Central India				
Gwalior, Madhya Pradesh	∑HCH	3.5×10^{-9} to 2.7×10^{-8}	1.2×10^{-8} to 9.1×10^{-8}	Kumar et al. (2018)
	∑DDT	7.4×10^{-10} to 1.6×10^{-8}	2.5×10^{-9} to 5.3×10^{-8}	
Korba, Chhattisgarh	α-HCH	7.7×10^{-9} to 8.4×10^{-8}	4×10^{-8} to 4.3×10^{-7}	Kumar et al. (2014a, 2014b)
	γ-HCH	1.4×10^{-9} to 1.6×10^{-8}	7.3×10^{-9} to 8.3×10^{-8}	
	op-DDT	5.7×10^{-10} to 1.8×10^{-9}	3×10^{-9} to 9.1×10^{-8}	
	pp-DDT	3.9×10^{-10} to 5.6×10^{-8}	2×10^{-9} to 2.9×10^{-7}	

41.6 Ecological Impact of Pesticides on Soil Microbial/ Enzymatic Properties

Pesticides are made up of complex organic molecules and are very useful to restrict the insect-pests, pathogens and weeds in diverse kinds of crops as prophylactic and curative modes to rescue the crop from the damages intended to be. But being an external source of synthetic chemical, their long-term and repeated applications in soil have often not found to be encouraging. Though their responses did not follow the same trend, while sometimes the effect on certain soil microbial parameters was promoted, whereas few others were depressed at a certain dose lingering over a phase.

In rice, the long-term effect of continuous application of chlorpyrifos (0.5 kg ha^{-1}) on non-target groups of soil microbes and nematodes was studied by Kumar et al. (2017), which indicated that asymbiotic aerobic nitrogen fixers, nitrifiers, denitrifiers, gram-positive and spore-forming bacteria were significantly reduced by nearly 0.25 to 2-fold by this application, whereas populations of heterotrophic, aerobic, anaerobic, oligotrophic and copiotrophic bacteria remain unchanged over the period. Additionally, plant-parasitic nematode species, *Meloidogyne graminicola* and *Hirschmanniella* spp. were also found to be reduced under this treatment, revealing the overall expected changes under common insecticide application in rice fields. In another study, fungi, actinomycetes and phosphate-

Table 41.9 HQ values of some pesticides in various soils of India

Place	Pesticide	Adult (mg/kg/day)	Children (mg/kg/day)	References
Southern India				
Idukki, Kerala	∑DDT	6.24×10^{-11} to 2.49×10^{-4}	8.09×10^{-11} to 3.23×10^{-4}	Joseph et al. (2020)
	∑endosulfan	1.68×10^{-10} to 2.27×10^{-5}	2.178×10^{-10} to 3.08×10^{-5}	
	Endrin	1.83×10^{-10} to 3.39×10^{-4}	2.37×10^{-10} to 4.39×10^{-4}	
	Dieldrin	9.15×10^{-11} to 1.007×10^{-3}	1.186×10^{-10} to 1.305×10^{-3}	
	γ-HCH	8.81×10^{-12} to 5.94×10^{-5}	1.14×10^{-11} to 7.71×10^{-5}	
Eastern India				
Indo-Gangetic area	∑DDT	1.35×10^{-5}	–	Mitra et al. (2019)
	∑HCH	3.55×10^{-7}	–	
Central India				
Gwalior, Madhya Pradesh	∑HCH	1.8×10^{-7} to 1.1×10^{-5}	6×10^{-7} to 3.7×10^{-5}	Kumar et al. (2018)
	∑DDT	2.2×10^{-5} to 2.7×10^{-4}	7.7×10^{-5} to 9.1×10^{-4}	
Korba, Chhattisgarh	α-HCH	1.5×10^{-7} to 1.7×10^{-6}	8×10^{-7} to 8.6×10^{-6}	Kumar et al. (2014a, 2014b)
	γ-HCH	4.2×10^{-6} to 4.8×10^{-5}	2.2×10^{-5} to 2.5×10^{-4}	
	op-DDT	3.4×10^{-6} to 1×10^{-4}	1.7×10^{-5} to 5.3×10^{-4}	
	pp-DDT	1.2×10^{-5} to 1.7×10^{-3}	6.2×10^{-5} to 8.8×10^{-3}	

solubilizing bacteria were most disturbed by imidacloprid application in rice field soil, while among microbial activities measured β-glycosidase, fluorescein diacetate hydrolase, acid phosphatase and urease were more hampered due to imidacloprid application (Mahapatra et al. 2017). Elevated CO_2 played a major role in Chlorpyriphos dissipation in rice fields and its impact on soil ecological behaviour (Adak et al. 2016). Chlorpyriphos degraded faster from rice soils under elevated CO_2 (700 ppm) after spraying at 500 g a.i. ha^{-1} at maximum tillering stage, whereas microbial biomass carbon and dehydrogenase, fluorescein diacetate hydrolase, urease, acid and alkaline phosphatase activities also positively responded to elevated CO_2.

Das and Mukherjee (2000) experimented with four studied insecticides (BHC, phorate, carbofuran and fenvalerate) applied in their recommended doses in laterite (alfisol) soils showed that BHC and phorate in particular stimulated the growth of aerobic non-symbiotic N_2-fixing bacteria and phosphate-solubilizing microorganisms and also their biochemical activities, and thus more of available N

(NH_4^+ and NO_3^-) and P in soil with a shorter persistency in soil varied between 8.8–20.6 days.

Incorporation of two pre-emergence herbicides in the peanut field was found to stimulate the activity of soil microbial biomass carbon, fluorescein diacetate hydrolysing activity, alkaline phosphatase and ammonification rates, while dehydrogenase activity, acid phosphatase, nitrification rate and available phosphorus were adversely affected. However, urease remains almost unchanged. Dissipation of both pendimethalin and oxyfluorfen followed first-order reaction kinetics with a half-life ($T_{1/2}$) ranged between 13.7–20.1 and 21.5–27.4 days, respectively (Saha et al. 2015). In another study, few important soil bioindicators were assessed applying two post-emergence herbicides (imazethapyr and quizalofop-p-ethyl) at three doses: half recommended rate (HRE), recommended rate (RE) and double recommended rate (DRE). Increased alkaline phosphatase and decreased acid phosphatase activities while increment of both ammonification and nitrification processes indicates that herbicides had detrimental effects on ammonia-oxidizing microorganism and denitrification process (Saha et al. 2016a).

Foliar application of tebuconazole at field rate (FR) and doubling the field rate (2FR) resulted in a short-lived and transitory toxic effect while the disturbance was persistent at 10FR. It showed a stimulating effect on soil microbial activity as evidenced by increased ammonification and nitrification rates and increased soil microbial biomass. However, it was more toxic to soil ergosterol which is the indicator of the presence of viable fungi (Saha et al. 2016b).

Increased soil respiration rate (evolution of CO_2) was observed by the application of glyphosate to a tune of 10–15% throughout 32 days as reported in Brazilian soil by Araújo et al. (2003). Similarly, both C and N mineralization rates enhanced from the first day to fourteenth day after glyphosate addition without affecting soil microbial biomass (Haney and Senseman 2000) inferred that glyphosate seemed to be degraded faster by microbes, and did not disturb the microbial activity.

The common herbicide bispyribac sodium is largely used in the rice field. While studying its non-target effect on soil microbes, Kumar et al. (2020) found that MBC and dehydrogenase, alkaline phosphatase and urease enzyme activities along with heterotrophic bacteria, actinomycetes and fungal populations notably decreased in bispyribac sodium applied rice fields in two rates: 35 g ha^{-1} and doubling its rate, i.e. 70 g ha^{-1} treated soils.

Cotton being a large consumer of pesticides was also taken into account while assessing its soil ecological impact after Acetamiprid (insecticide) application (Singh et al. 2015a, b). The study reported that Acetamiprid showed declining effects on nitrate reductase, arginine deaminase and urease activities but dehydrogenase rate was increased after a 3 years' long field experiment.

Across the world, many studies in similar directions have been conducted but no conclusive remark was made about universal inhibitory/promoting effects of pesticides on soil biota and their responses. Majorly the pesticide exhibited transitory effects although long-lasting effects were prominent in few occasions as well. Rather, by and large, they inferred that the effects observed were varied due to soil type(s) including soil pH, moisture, temperature, salinity, etc., nature of pesticide(s), i.e. pre- or post-emergence, dose and frequency of pesticide(s), organic and other agro-management applied, duration of the crop/cropping system, and persistency of that pesticide molecules in the field. Many researchers have opined that the rate of dissipation of any pesticides may have a close association with its ecological impact in terms of soil microbial responses, enzyme activity and microbial populations.

41.7 Novel Control and Remediation Method to Countermeasure the Pesticide Pollution in Soil

In the last two decades or so, there have been many trials conducted overall the world that particularly emphasized the remediation of pesticide residues in soil. Since to counteract and nullify the traces of pesticide molecules after a crop harvest has never been easy considering its degradation and dissipation that finally determines the longevity of the molecules which in some cases resides year after year.

To avoid this scenario, the use of biopesticides, which are mostly natural product-based, and not harmful to soil biota are increasing. The broad group of biopesticides can be defined as the natural substances that can be derived from microorganisms (microbial pesticides), plant-derived that contain added genetic material (plant-incorporated protectants—PIPs), and other naturally occurring products (biochemical pesticides) that offer pest control (Gopal et al. 2007). These have been a prominent replacement of chemical pesticides and have been adopted as an eco-friendly solution of pest management in many countries including India. *Bacillus thuringiensis* (Bt), *Baculo* viruses, *Trichoderma*, *Azadirachta indica* are some of the popular and frequently used biopesticides, and the leading multinational companies involved in the biopesticide markets are Bayer Crop Science Ag, Marrone Bio Innovation, Certis USA LLC, The Dow Chemical Company, Monsanto and few others which are expected to reach $10.24 billion by 2025.

Besides, several plant growth-promoting bacteria (PGPR) which is a consortia of beneficial microorganisms having multifunctional abilities including pest management and sustaining crop growth applied as seed and soil inoculations also gained interest as an alternative choice of chemical pesticides. The dominant microbes under PGPR consist of *Bacillus subtilis*, *Pseudomonas fluorescens*, *Paecilomyces lilacinus* and *Beauveria bassiana.* Another such intervention was Bt crops, where crystal toxin protein transferred through transgenic mode produced by leaves, stems and roots releasing large quantities of toxins into the soil ecosystem (Meena et al. 2020). A case study showed that Bt cotton has produced 50% gain in profit from 2002 to 2008 among smallholders of central and southern India with an increase of 24% in cotton yield per acre by reduced pest damage (Kathage and Qaim 2012).

Herbicide-resistant crops are another genetic intervention that can reduce the load of pesticide usage and counteract the negative effects that arise with it. The glyphosate-resistant rapeseed (*Brassica napus*) containing the “pat” gene is such an example that has been found to influence some dominant groups of soil bacteria like *Bacillus*, *Micrococcus, Variovorax, Flavobacterium* and *Pseudomonas* (Medina et al. 2003). However, the effect of herbicide-resistant crops on soil ecosystems may

Table 41.10 Some latest/advanced techniques used for remediation of pesticide-generated soil pollution

Techniques/methods	Applications	References
Mycoremediation	• A kind of bioremediation in which fungi technology is used to decontaminate the environment • A cheap, efficient and environment-friendly way to remove pollutants • Some spp. of fungi have been used for bioremediation of organophosphate pesticides	*Aspergillus niger*, *Aspergillus fumigatus* (Pandey et al. 2014) *Cladosporium cladosporioides* (Gao et al. 2012) *Penicillium raistrickii*, *Aspergillus sydowii* (Alvarenga et al. 2014)
Biochar	Biochar applied (50 g kg^{-1}) in chlorothalonil (CHT)-polluted soil resulted in increased denitrification rates and abundance of denitrifiers (*Enterobacter* and *Pseudarthrobacter*)	Su et al. (2019)
Green silver nanoparticles	Green synthesis of silver nanoparticles (AgNPs) using purple-coloured rice leaves' extract is suitable as a broad-spectrum pesticide, and effective against disease-causing pathogens in rice like *Rhizoctonia solani* and *Xanthomonas oryzae* pv. *Oryzae* and *Helminthosporium oryzae*	Adak et al. (2020)
Advanced oxidation under electrokinetic remediation	TritonX-100 (TX-100) in advanced oxidation under electrokinetic technology (EK) was used for decontamination of organochlorine pesticides in an industrial wasteland and reported for good removal efficiency	Suanon et al. (2020)
Engineered endophytic bacteria	• It is a promising new technology that improves the phytoremediation of water-soluble, volatile organic pesticide derivatives • Trichloroethylene (TCE)-degrading bacteria is found to protect host plants against the phytotoxicity of TCE and contributed to a decrease in TCE evapotranspiration	Barac et al. (2004)
Metagenomics	It brings deeper insights into the abundance and activity/response of degrading microorganisms within pesticide-polluted rhizosphere consortia, and also helps in tracking compounds released by plants under such a specialized environment	Mackova et al. (2006) Singer et al. (2003)

differ and inconsistent majorly due to the different transgenic plants-governed root exudates that altered the rhizosphere environment (Liu et al. 2005). Some latest/advanced techniques used for remediation of pesticide-generated soil pollution are given in Table 41.10.

41.8 Conclusion

Soil and sediments are the most important natural resources for the terrestrial and aquatic environment. Extensive and inevitable use of pesticides may contaminate both of these natural resources. With this background, this chapter gathers a detailed source of information about the source, occurrence, distribution of pesticide pollution in soil and sediment of India along with the causes and impact of pesticide pollution and possible remediation measures. Though an extensive information is available about the occurrence of pesticides in soil and sediment of India, the available data are highly fragmentary and more concentrated on OCPs, particularly DDT and HCH. These are mostly banned pesticides, hence it is also advised that further study should be focused on the occurrence of new-generation pesticides which are mostly popular now-a-days in the Indian context. This compilation also indicates that despite low pesticide consumption in India, frequent occurrence of pesticide residues in soil and sediment is due to indiscriminate past use and illegal present use, is indeed a matter of concern. Though extensive study has been carried out for agricultural, urban soil and sediment, limited information is available about the pesticide contamination in virgin (viz. forest and Himalayan region) soil which can be used as a reference level of contamination. This high level of contamination may be caused with the incorrect dosage of pesticides application, lack of awareness and education amongst the farmers, lack of interest of the public agencies for initiating the monitoring and awareness programme. Use of environment-friendly pest control strategies, integrated pest management (IPM), advanced pesticide delivery mechanism like new-generation controlled release formulation, appropriate guiding to the farmers by extension officials, along with stringent rules and regulations regarding the banned pesticides may help in reducing the level of pesticide pollution. Proper understanding of the risk associated with the pesticides will help the stakeholders to regulate its misuses and to know the ill-effect of these pesticides.

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Climate-Smart Soil Management: Prospect and Challenges in Indian Scenario

42

Aritra Kumar Mukherjee and Kaushik Batabyal

Abstract

The impact of climate change on agriculture is a major constrain to achieve the global food security. It has become a global challenge to deal with the strong link between soil degradation, climate change, and food insecurity. Climate-smart soil management is a smart approach of maintaining a soil healthy through enhanced carbon loading under changing climate. Soil is a precious gift of nature and is the integral to the function of all terrestrial ecosystems, viz., crop production, environmental filter, and climate regulation. Soil has great potential of mitigating emission of greenhouse gases, which enable emerging research and information technology for a broader inclusion of soil in greenhouse gas policies. It is, therefore, important to restore degraded soil and decertified ecosystems to create a carbon positive one. Studies across the globe indicated that soil organic carbon (SOC) sequestration could be enhanced through adaptation of climate-smart soil management practices to address the global goals on reduction in greenhouse gas emissions and improvement of crop productivity. Therefore, increasing attentions are being given by different policy and research organizations towards management of soil under changing climate to meet the global pressure on food security. In this chapter, we aim to provide an overview on different prospects and challenges for adopting climate-smart soil management techniques under Indian scenario.

Keywords

Climate-smart soil management · Greenhouse gas · Soil organic carbon · Food security

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42.1 Introduction

Agriculture is the key to meet basic needs and livelihoods for more than 70% of the world's poorest people and is the predominant economic industry in many countries (Economy 2014). This agricultural system in the world has been facing tremendous pressure on the use of resources largely due to climate change and environmental stresses. Increase of mean temperature, changes in rain patterns, increasing frequency and intensity of extreme events, sea level rise and salinization, perturbations in ecosystems are the clear indications of that and have profound impacts on agriculture (HLPE 2012; Thornton 2012). The InterGovernmental Panel on Climate Change (IPCC), in its Fifth Assessment Report, has warned that global climate has been changing and it would continue to happen in future (Field and Barros 2014). Scientific community stated that due to climate change the temperature will increase globally, and this will hamper agricultural productivity significantly. The yield of crop decreases due to climate change up to 35% for rice, 20% for wheat, 50% for sorghum, 13% for barley, and 60% for maize depending on the location and future climate scenarios (Porter et al. 2014). The Food and Agriculture Organization (FAO)-2018 report clearly indicated a continuous rise in world hunger due to climate change impacts on agriculture (State of Food Security and Nutrition in the World 2018).

Agriculture sector in India is climate-sensitive and highly vulnerable due to widespread poverty, dependence of about 50 per cent of its population on agriculture for livelihood. Therefore, increasing weather variability and climate change have become major barriers to achieving food security and alleviating poverty in India. In spite of the success of Green Revolution in 1965 in transforming Indian agriculture by making self-sufficient in food grain production, continued intensive use of the same technologies, practicing conventional agriculture, and the consequent environmental problems such as groundwater depletion and deteriorating soil health have been adversely affecting the Indian agricultural sector. Among the 119 countries, India ranked 100 and was classified in the "serious category" with a score of 31.4 in the 2017 Global Hunger Index (Von Grebmer et al. 2017). Therefore, nations need to act sincerely towards achieving the Sustainable Development Goals (SDG) on food security and improved nutrition (State of Food Security and Nutrition in the World 2018).

Several suggestive ways have been highlighted for mitigating the impacts of climate change on agricultural production. Because of social, environmental, and economic problems arising from climate change, FAO has prompted a sustainable agricultural production system, i.e. Climate-Smart Agriculture (CSA) an alternative to conventional agriculture. Increased productivity, resilience to climate change, and reduced greenhouse gas emission are three basic pillars of CSA. It improves the efficiency of natural resources, increased resilience and productivity of agriculture, and reduces greenhouse gas emissions (Totin et al. 2018). The CSA is, therefore, being embraced globally as an approach to transform and protect the agriculture sector from the impact of changing climate scenario.

Emission of greenhouse gas (GHG) caused by the human activities such as burning of bushes, deforestation, etc., has globally influenced natural and social systems (Lamboll et al. 2017). Agriculture land is a major source of all three biogenic GHGs, viz., carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Soils contribute a major share (37%, mainly as N_2O and CH_4) of agricultural emissions (Tubiello et al. 2015). Improved climate-smart soil management practices not only help to reduce the emission of GHG from the soil but sequester more carbon and tighten the soil nitrogen cycle. These may lead to enhance soil fertility and productivity; increase soil biodiversity, reduce erosion, run off, water pollution, and can help to buffer crop and pasture system against the impact of climate change (Smith 2012).

This book chapter evaluates the importance of CSA technologies on soil management for maintaining and/or improving its eco-functionalities towards achieving the sustainable development goals (SDG) to ensure food security through mitigating the adverse effects of climate change on agricultural production and productivity in India.

42.2 Climate-Smart Agriculture for Food Security

Agriculture is an important economic sector and major employment source in Asia. About more than 20% of the population in these regions is facing the problem of food insecurity (Wheeler and Von Braun 2013). It is estimated that, by 2050, population will reach to 9.7 billion and will require about 70% more food to feed human than what is consumed today (Fig. 42.1). According to Alexandratos and Bruinsma (2012) the world will need to respond to an increased demand of global

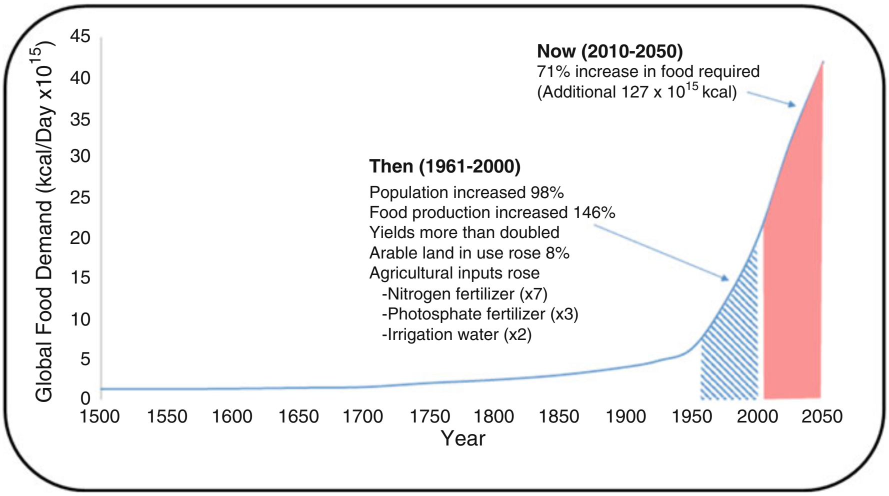

Fig. 42.1 Framing the food security challenge (adopted from Keating et al. 2014)

food security by 2050 due to population and income growth. Henceforth, it seems to be a grand challenge before us to stabilize the issue of sustainability (McGuire 2015). Therefore, agricultural production will have to increase for the purpose, which is supposed to be the major driver of economic growth across the globe.

Intergovernmental Panel on Climate Change (IPCC), in their latest report, stated that agricultural growth and food security already being hampered by climate change (Porter et al. 2014). Global yields of maize and wheat decreased 3.8% and 5.5%, respectively, due to adverse effect of climate (Lobell et al. 2011). Natural calamities such as drought, flooding, high maximum temperature, heavy rainfall are already occurring in many regions and pose a threat to food security for both rural and urban populations by reducing agricultural production and income (Porter et al. 2014). Agriculture itself is a principle contributor to planetary warming. Emission of CO_2 and non-CO_2 greenhouse gases (GHG) due to conventional agricultural practices is very important in fueling the climate change. Uses of synthetic fertilizer, paddy cultivation, enteric fermentation, biomass burning are the highest emitting agricultural practices. It is estimated that, about 2.5 billion people globally dependent on small scale farming which is contributing nearly 19–29% of GHG's emission and is vulnerable to climate change (Niles et al. 2017). In view of impending growth of agricultural produce for the purpose of food security, there has been an increase in emission of greenhouse gases. Time has come to take major initiative to not only meet the increasing food demand, but also safeguard the quality of the environment for better sustainability. Direct and indirect effects of human-induced climate change on food security are given in Fig. 42.2.

42.2.1 What Is Climate-Smart Agriculture (CSA)?

Climate-smart agriculture (CSA) can be stated as a way of dealing with the challenges of climate change and food security for achieving SDGs (FAO 2010). After the global food crisis in 2007-08, food security remained a volatile issue for life under poverty in rural areas and those whose main income source was agriculture. Agricultural production needed a new direction to address multiple interlinked challenges. Development agencies such as United Nation's Food and Agriculture Organization (FAO) and the World Bank raised concerns that effort is to be needed to reduce poverty, especially for the rural poor. In pursue of concern, the concept was first launched by FAO in 2010 in The Hague Conference on Agriculture, Food Security and Climate Change (FAO 2010).

42.2.2 Principles of Climate-Smart Agriculture (CSA)

The CSA has three focal areas, viz., (1) agronomic and economic productivity, (2) adapting and building resilience to climate change, and (3) Climate change mitigation (Palombi and Sessa 2013). The key concept related to raising productivity is increasing food production sustainably from existing farmland while minimizing

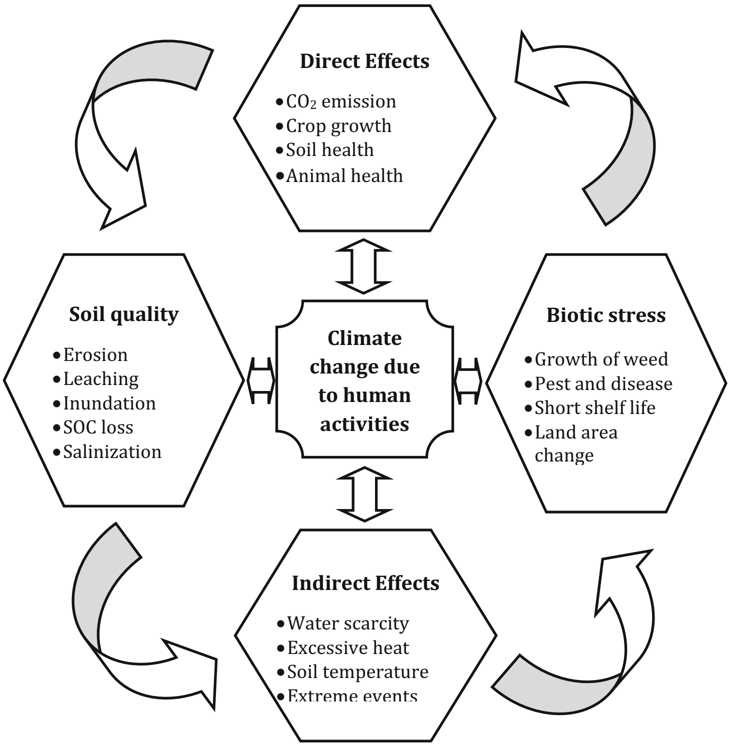

Fig. 42.2 Effects of human-induced climate change on food security

pressure on the environment (Totin et al. 2018). This first principle is strongly connected to the second one. Adapting and building resilience to climate change ensures food sufficiency despite unsuitable conditions. According to Rockefeller Foundation 2009 (Rockefeller 2009) climate resilience is defined as the capacity of an individual, community, or institution to respond dynamically and effectively on climate impact circumstances while continuing function at an acceptable level. This principle of CSA can only be achieved through adopting third principle of CSA, which entails different soil management practices like sequencing carbon in the soil, reducing greenhouse gas emission (GHG), and enhancing natural resource base (FAO 2010). Reducing emissions; avoiding or displacing emissions; removing emissions are the three major options to mitigate climate change. Therefore most important premise of CSA is the building of healthy soil (Stabinsky and Lim 2012), through increasing organic matter content of the soil (Blanco-Canqui et al. 2014). The CSA aims towards achieving all three objectives; but it is not feasible to have “triple wins” under every circumstance. However, to achieve these three principles, we need to take a flexible approach, working with the various narratives, instead of working around them (Chandra et al. 2018).

42.3 Climate-Smart Soil

Agriculture land is a major source of all three biogenic GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Soils contribute a major share (37%, mainly as N_2O and CH_4) of agricultural emissions (Tubiello et al. 2015), while land use contributes 25% of the total global anthropogenic GHG emission (Smith et al. 2014). It was estimated that, total non-carbon-dioxide (CO_2) greenhouse gas (GHG) emissions from agriculture in 2010 are 5.2–5.8 gigatonnes of CO_2 equivalent per year (Smith et al. 2014), making up about 10–12% of global anthropogenic emissions (Tubiello et al. 2013). Decrease in GHG emission and sequestering carbon through improved soil management practices increases soil organic matter (SOM) content and tightened the nutrient cycle in the soil, which in turn helps to improved fertility and productivity, increased soil biodiversity, and can help to develop resistance capacity against adverse effect of climate change.

The SOM primarily contains organic carbon which acts as a sink for atmospheric carbon. It helps to improve soil structure by binding soil particles together as stable aggregate, important for nutrient availability in soil and also has an impact on the overall biological resilience of agro-ecosystems. Plant nutrients present in soil in the form of positively charged ions (i.e., cations). Apart from this, during decomposition of SOM the multitude of any organisms in the soil food web release nitrogen (in the form of ammonia ions), potassium, calcium, magnesium, and a range of other nutrients which is necessary for plant growth. The negative charges on the surface of the clay particles and organic matter attract cations and thus plants obtain many of their nutrients from soil by cation exchange where exchange of hydrogen ions with the cations adsorbed on the soil particles was occurred by the root hairs of plant. Mechanical soil disturbance such as plowing is detrimental for buildup of organic matter in soil. It was observed that improved management practices can reduce GHG's emission and increase soil carbon stock to soil. Soil carbon sequestration is one of a few strategies that could be applied at large scales and at low cost (Ciais et al. 2014). It will not only stabilize climate but will also make agricultural production more sustainable and maintain the ecosystem services that are supported by soils. Globally the French government has suggested increasing soil C concentration of soil carbon in a large portion of agricultural soils by 0.4% per year, in accordance with the Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) negotiations in December 2015. This would lead to an increase in C sink of 1.2 pentagrams' (Pg) of C per year (Paustian et al. 2016).

Carbon sequestration potential of soil depends on various factors. Assessment of carbon sequestration rates should always refer to specific carbon pools due to different turnover rate of carbon. For instance, carbon accumulated in the initial years is highly oxidizable and as the time passes it becomes more stable. In addition, to capture the effects of climate, data analysis should be carried out at the level of agro-ecological zones (Corsi et al. 2012). It is necessary to have benchmark or some reference base for similar soil type under same climatic conditions while assessing the effects of soil management practices. When comparing soils disturbed by human activities, undisturbed soils under natural vegetation should be used as a benchmark.

Apart from this, it is necessary to have the capacity to monitor and measure GHG reductions rate with accuracy and at relatively low cost while implementing effective soil-based GHG mitigation strategies.

42.4 Global Carbon Cycle and Carbon Pool

Carbon is the fourth abundant element in the universe and is necessary for life, as it is the backbone of all kinds of structural and functional compounds. It is important to know about global carbon cycle and its disturbance due to several anthropogenic activities for mitigating climate change. Concentration of CO_2 and other greenhouse gases (GHG) in the atmosphere has been increased drastically. Presently the concentration of carbon dioxide (CO_2) is increasing at a faster rate of 1.7 ppmv yr.$^{-1}$ or 0.46% yr.$^{-1}$. Sharp increase in concentrations of methane (CH_4) and nitrous oxide (N_2O) has also observed in same manner (Change 2007). The anthropogenic activities, interaction of biogeochemical and climate processes on the global carbon cycle, and interaction among principal carbon pools will further lead to increase in concentration of atmospheric CO_2. Anthropogenic activities such as combustion of fossil fuel, deforestation, land use change, soil cultivation, etc., are responsible for emission of CO_2. Presently, 7 Pg C yr.$^{-1}$ is emitted by fossil fuel combustion, while 1.6 Pg C yr.$^{-1}$ by deforestation, land use change, and soil cultivation (Pacala and Socolow 2004). The average global surface temperature seems to increase by 0.8 $^\circ$ C due to this anthropogenic enrichment of GHGs in the atmosphere (Change 2007). These may affect soil organic carbon (SOC) pool and its structural stability, disrupt cycles of water, carbon (C), nitrogen (N), phosphorus (P), sulfur (S), and other elements.

Three forms of carbon are present on earth, viz. (1) elemental (derived from geological sources), (2) inorganic (present in carbonate minerals such as calcite, dolomite, and gypsum, and comprises primary and secondary carbonates. Due to weathering of parent material primary carbonates are formed, while secondary carbonates are formed through the reaction of atmospheric CO_2 with Ca^{+2} and Mg^{+2}), (3) organic (Nieder and Benbi 2008). The soil inorganic carbon pool is an important constituent in soils of arid and semi-arid regions. Different organic carbon forms are mainly decomposed or partially decomposed products of plants, animals, and microbes. Interconnection of these three forms of carbon (elemental, inorganic, and organic) in a cyclic manner occurring in the reservoirs of the Earth through biogeochemical processes such as photosynthesis, respiration, burning, burial of organic matter, decomposition, and weathering could be defined as carbon cycle (Mandal et al. 2020a).

Global carbon pools are composed of five principles, of which the oceanic pool is the largest, followed by the geologic, pedologic (soil), biotic, and the atmospheric pool (Fig. 42.3). Carbon circulates among all these inter-connected pools. The smallest among the global C pool is biotic C pool and pedologic with the biotic carbon pools together are called the terrestrial C pool.

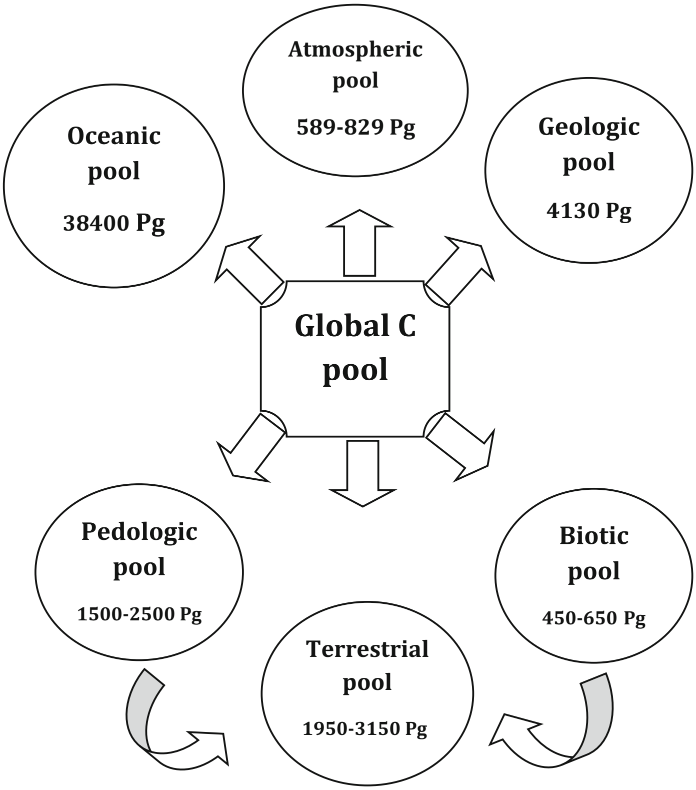

Fig. 42.3 Principle of global carbon pool (data taken from Ciais et al. 2014)

Soil is the largest reservoir of carbon (C) and it holds three times more carbon than the atmosphere (Sanderman et al. 2017). Next to oceanic pool, soils store about 3.5 times higher than C present in vegetation and about 2.5 times more than atmospheric C (Ciais et al. 2014). Soil organic carbon (SOC) is a primary indicator of soil health and plays a crucial role in climate change mitigation and adaptation (Lorenz and Lal 2016). The dynamic of agricultural SOC is regulated by the balance between carbon inputs (e.g., crop residues and organic fertilizers) and outputs (e.g., decomposition and erosion) under long-term constant environment and management conditions. Climate is generally regarded as the dominant control over soil carbon dynamics and this balance has been dramatically altered by climate change (Wiesmeier et al. 2016). Global warming and land uses in cultivation as agricultural management practices are also responsible behind decrease in OC stocks from soil (Li et al. 2007).

42.5 Climate-Smart Soil Management

Recently scientist are focusing on the holistic management of natural resource base for long-term productivity to meet the demand of food security and not only maximizing the yield in short-term. This can only be possible by adapting the following climate-smart management strategies.

42.5.1 Management of Soil Organic Carbon Pool

Managing soil carbon will help to enhance soil fertility, improving food production in sustainable way, maintaining clean water, and reducing CO_2 concentration in atmosphere. Plowing of land for cultivation is responsible for loss of carbon from soil and turns soil susceptible to erosion. After harvest of crop, leaving crop residues in the field could help to increase soil carbon content and make soil resistant to erosion, but the benefits are lost if the biomass is plowed before cultivation of next crop, because microorganisms quickly degrade residue C to CO_2. Essential nutrients are also disappearing from soil with the depletion of soil organic carbon (SOC). Thus, farmers require more fertilizer, irrigation, and pesticides to preserve yield, though beneficial effect of carbon cannot be replaced with increase fertilizer level. Apart from this, in India, farmer's sell top soil up to 1 m depth to brick factory for meeting the demand for housing. So, now it is top priority to identify alternative way for brick making and use of top soil from cultivated land should be banned. Government should come forward and create policies or provide financial incentives to farmers and provide education along with implementation of different extension programs.

42.5.1.1 Soil Carbon Sequestration

The term "soil carbon sequestration" implies controls on soil carbon balance with increasing the rate of carbon additions through plant residue, manure, or other organic waste and decreasing the rate of carbon loss via decomposition (e.g., reducing soil disturbance). Hence, carbon stocks can be increased by either increasing organic matter inputs or by reducing decomposition rates, or both. That leads to net removal of carbon from the atmosphere (Paustian et al. 1997). According to Lal (2004), carbon sequestration is a process by which transferring atmospheric CO_2 into the ocean, geologic basalt, vegetation, and soil and stored securely for a specific time period so that it is not reemitted immediately.

There are mainly two broad categories to sequestering carbon, viz. biotic and abiotic. In the biotic strategy involvement of plants and microorganisms is high to removing CO_2 from the atmosphere. Increasing use efficiency of water and energy is also another option for management of terrestrial C pool. Phytoplankton photosynthesis is one of the mechanisms that lead to sequestering C through forming some particulate organic material and deposited at the ocean. In terrestrial ecosystem, atmospheric CO_2 is stored into various plant parts (e.g., roots, leaves, brunches, etc.) and then fixed by photosynthesis process (Kishwan et al. 2009). Microorganisms utilize this stored carbon from plant roots and litters and incorporate biomass C into soil. Carbon sequestration also occurs in soil inorganic carbon as secondary carbonates but the rate of formation is low. Sufficient quantity of Ca^{2+} and Mg^{2+} must be present in soil which accelerates the formation of secondary carbonates. This process is cost effective and environment friendly. On the other hand, abiotic strategy is based on involvement of engineering techniques and physico-chemical reactions. Intervention of living organisms (plants and microbes) is less in this process. Oceanic and geological structures have got maximum attention in this process and considerable progress is being made through developing technologies for CO_2 capture (Lal 2008).

42.5.1.2 Soil C Sequestration Via Improved Management Practices

Global warming of climate is unambiguous and is the reason behind drastic climate change (Srinivasa Rao et al. 2017). Its effect in India is also observed over the past hundred (1901–2007) years. The warming trend in India was recorded to be 0.51 °C with increasing warming of 0.21 °C every 10 years since 1970 (Kumar 2009). Seasonal temperature variability, water stress, reduction in number of rainy days due to change in weather, natural calamities like flood, drought, and uneven distribution of rainfall create negative impact on yield of crop in India (NICRA 2013). Assuming that, in coming decades it will increase and its effect on crop production, fisheries, livestock management will immeasurable, particularly in developing countries where adaptive capacity is not strong enough to mitigate these effects of climate change. So, there is a need to development of strategies in the form of climate resilience agriculture which gives increment in productivity, source of income, food security, reducing GHGs emission to atmosphere and improves soil health. Several soil and crop management practices that enhance SOC pools are discussed below.

Land Use Management and Cropping System

Soils of forest and grass lands are mainly undisturbed soil and contained large fraction of their biomass below ground level. Natural ecosystem generally contains higher C stock than agricultural soil and depletion of C (0.5 to >2 Mg of C ha^{-1} $yr.^{-1}$) due to land conversion to crop land has been extensively documented (Ogle et al. 2005). Losses of C due to change in land use pattern not only decline from top soil, but also its depletion is documented in sub soil deeper than 20 cm to 100 cm (Sheng et al. 2015). Mandal et al. (2020b) also reported a gradual decrease in SOC and its several pools following the order horticultural orchards > cropland > uncultivated land. Rate of C sequestration on land use for agricultural purpose is also lower than land restore to grassland or forest and varies on 0.1–1 Mg C ha^{-1} $yr.^{-1}$. Hence, avoiding conversion of native ecosystems to agricultural land and restoration of marginal or degraded lands to perennial forest or grassland to increase soil C storage is a strong mitigation alternative (Fig. 42.4).

Modification of cropping system can increase rate of C sequestration in soil. It was observed that wheat–wheat crop rotation helps to build up of soil organic C up to 7.2% over wheat–chick pea rotation (Godde et al. 2016). This might be due to lower

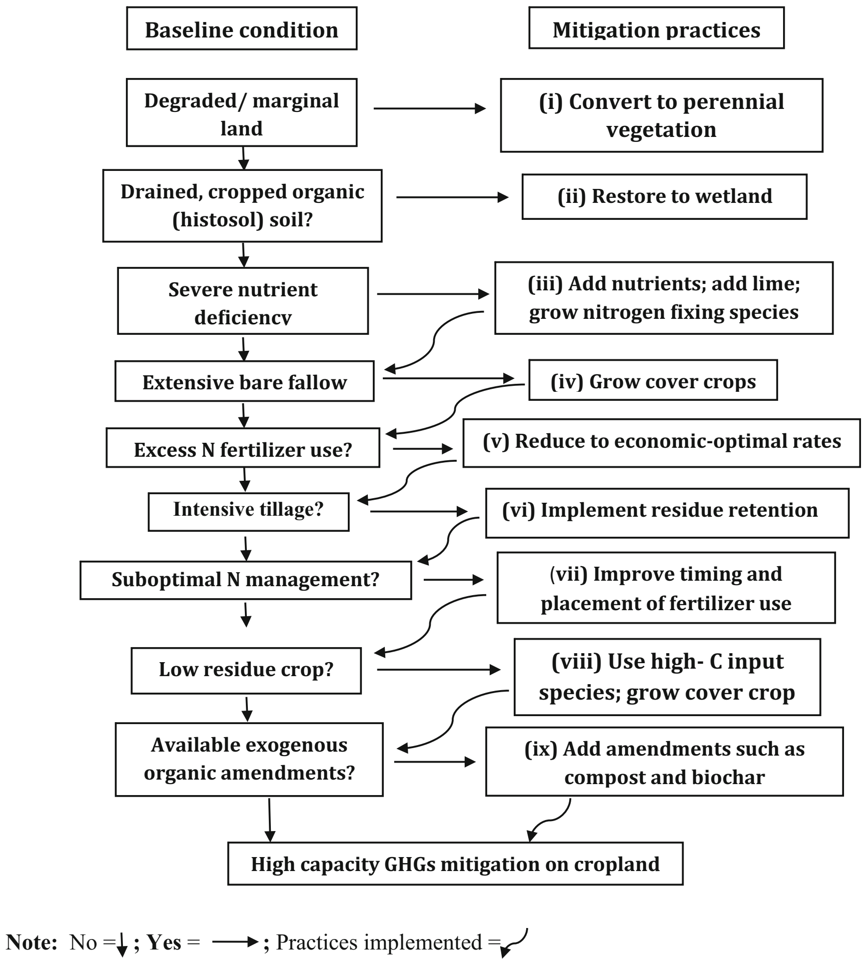

Fig. 42.4 Decision tree for cropland greenhouse gas mitigation practices (Adopted from Paustian et al. 2016)

biomass incorporation (47%) through chick pea than wheat. Mandal et al. (2008) found the efficiency of double-cropped rice system to build up of SOC stocks in sub-tropics of India which might be due to incorporation of lignin and polyphenol through crop residues and prolonged submerged condition resulting in stabilization of SOC mainly in recalcitrant form. Kukal et al. also reported the highest presence of easily oxidizable Walkley-Black SOC pool in soil under rice–wheat cropping system over maize–wheat cropping system in both Alfisol and Inceptisol. Change in cultivation of annual to perennial crop can increase C input below ground level that leads to C sequestration (Conant et al. 2001).

Cover Crop

Growing of leguminous as a cover crop can help to increase carbon pools and reduce C and N loss from soil (Singh et al. 1998). Tonitto et al. (2006) found that, cover crops reduce nutrient losses, including nitrate that is otherwise converted to N_2O in riparian areas and waterways. Higashi et al. (2014) showed that, cover cropping with conservation tillage (mainly no tillage) in sandy clay loam soil increased SOC concentration up to 22%. Growing of cover crop in sandy clay loam soil gives stability to soil aggregates, which in turn gives protection to SOC from mineralization (Unger 1997).

Tillage

Tillage practices impart significant effect on SOC pools. Plowing soil for cultivation purpose enhances oxidation rate, microbial activity, and exposure of soil to microbial decomposition through increasing soil aeration and temperature and that causes significant loss of SOC particularly from surface layer of soil (Purakayastha et al. 2008). Crop lands sequester C through less intensive tillage, mainly no tillage or zero tillage (Ogle et al. 2005), by less disruption of soil aggregate structures (Six et al. 2000). Conservation tillage enhances the proportion of macro-aggregates in soil, which gives physical protection to micro-aggregates associated with organic carbon (OC) and thus helps to mitigate C loss from crop land soil (Benbi and Senapati 2010). Mikha et al. (2013) found that, after 7 years continuing conservation tillage practices in crop land increase carbon content 19.7% in the top 30 cm soil layer, while Zhang et al. (2016) also noted a significant increase in SOC in the top 30 cm layer under zero tillage system as compared to conventional one.

Nutrient Management

Judicious application of fertilizers and manures is crucial for SOC sequestration (Liu et al. 2013). Datta et al. (2018) reported that, after 26 years cultivation of soil, TOC increases 31.3% over initial value under treatment receiving adequate application of fertilizers and manures whereas it decreases 8.8% under treatment excluding fertilizers and manures. He also observed that optimum application of NPK coupled with FYM enhances stratification ratio and liability index of carbon. Combined application of FYM and NPK lowers microbial proliferation rate which in turn lowers decomposition of C by soil microbes. Suman et al. (2009) found that, after 5 years cultivation of multi-ratooning sugarcane, the rate of C sequestration was increased by addition of organic manures over recommended NPK dose (Fig. 42.5).

Organic Farming

Organic matter plays an essential role in soil physical, chemical, and biological processes and that of soil organic carbon (SOC) is one of the most important indicators of soil quality and health. It helps to enhance soil fertility and crop productivity. Therefore, maintaining or increasing SOM is critical. As earlier stated that, soil is a component of terrestrial carbon (C) cycle and can be either source or sink of atmospheric carbon dioxide. So, their judicious management has a significant potential for mitigation of CO_2 and other GHGs emissions (Ghosh et al. 2012). Data

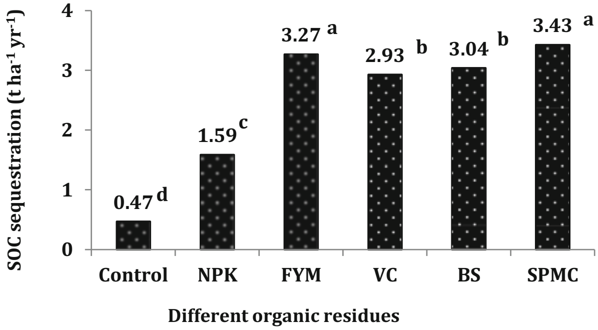

Fig. 42.5 Impact of different type of manures on SOC sequestration after 5 years of sugarcane cultivation. NPK: chemical fertilizer @ 150:60:60 and *FYM* farm yard manure, *VC* vermicompost, *BS* biogas slurry, *SPMC* sulphitation press mud cake all manures applied @ 10 t ha^{-1}. Different lowercase letters indicate significant differences ($P < 0.05$) (Adopted from: Suman et al. 2009)

received from long-term field experiments conducted in hot humid sub tropic Indo-Gangetic plains of eastern India showed that application of FYM, paddy straw, and green manure as a supplement with NPK not only added organic carbon in the soil but also increased plant C inputs in the soil through root residue, stubble, rhizodeposition (Table 42.1), with increase in yield (Table 42.2) (Ghosh et al. 2012). Thus, implication of balanced organic inputs is necessary to maintain both the soil C content as well as productivity.

Addition of Crop Residues and Mulching

Addition of crop residues affects on temperature, aeration, and moisture content of soil. Microbial activities in soil are also influenced by addition of crop residues. Significant increase in rate of C sequestration was observed by several scientists by application of crop residues in soil. Benbi et al. (2012) reported that, after 11 years of rice–wheat cropping system, significant increase in SOC was observed in the treatment receiving farmyard manure (FYM) along with rice straw (RS), followed by solely application of FYM, RS and the lowest value was recorded under treatments with no organics (Fig. 42.6). Paddy straw contains higher amount of lignin and polyphenol with higher C:N ratio, that leads to augmenting recalcitrant passive carbon pool in soil (Majumder et al. 2008). Das et al. (2018) also suggested that adoption of zero tillage with crop residue in rice–wheat and maize–wheat cropping system in Indo-Gangetic plains could be a possible way to enhance SOC sequestration in soil.

Mulch is a layer of material (usually but not exclusively organic in nature) applied to the surface of soil to protect soil moisture, reducing weed growth, increasing C storage capacity and mitigates GHGs emission from soil. Adhikari et al. 2017 mentioned higher SOC stock in zero tillage with using rice straw as mulch applied soil over conventional tilth soil.

Table 42.1 Cumulative C inputs in soils through different treatments (Adopted from Ghosh et al. 2012)

Treatment	Mg ha^{-1}						
	Stubble biomass C	Root biomass C	Rhizodeposition C	Aquatic biomass C	Crop C input	FYM/PS/GM C	Cumulative C input
Control	1.52	10.6	11.8	13.3	37.2	0.0	37.2
NPK	3.04	24.5	29.6	13.3	70.4	0.0	70.4
NPK + FYM	3.42	27.0	34.2	13.3	77.9	9.5	87.4
NPK + PS	3.42	26.4	33.3	13.3	76.4	8.0	84.4
NPK + GM	3.23	25.8	32.5	13.3	74.8	6.3	81.1

Note: *FYM* farmyard manure; *PS* paddy straw; *GM* green manure

Table 42.2 Yield of Kharif rice and sustainable yield index after 25 years of cultivation with organic and inorganic treatment combinations (Adopted from Ghosh et al. 2012)

Treatment	Yield (t ha^{-1})	Sustainable yield index (SYI)
Fallow	–	–
Control	1.5^{c}	0.234^{e}
NPK	2.0^{c}	0.616^{d}
NPK + FYM	3.2^{a}	0.684^{a}
NPK + PS	2.6^{b}	0.638^{c}
NPK + GM	3.3^{b}	0.669^{b}
SEm (±)	0.169	–

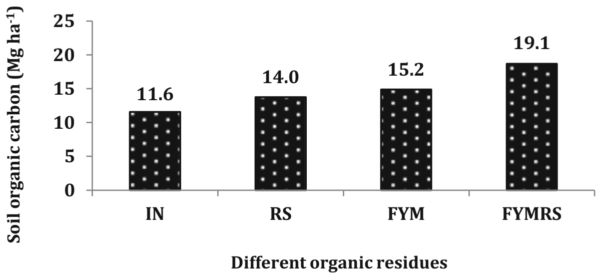

Fig. 42.6 Soil organic carbon stocks in 15 cm layer under different residue management practices. *IN* absence of organic amendments; *RS* rice straw; *FYM* farm yard manure; FYMRS: FYM + RS (Adopted from Benbi et al. 2012)

Irrigation

Judicious application of irrigation water in drought prone area can enhance biomass of crop, which in turn increase SOC concentration in soil (Smith 2008). Increase in water use efficiency (WUE) during irrigation can decrease hidden costs of carbon with increasing SOC concentrations in grassland areas (Conant et al. 2001). Zhang et al. (2016) found that, mid-season drainage under rice cultivation decreased SOC accumulation nearly 16%, while in another experiment (conducted from 2001 to 2019) on rice cultivation he observed that, no drainage during mid-season increases SOC content by 12 kg C ha^{-1} $yr.^{-1}$.

Soil C sequestration via exogenous C inputs

Addition of plant-derived C from external sources such as composts or biochar can increase soil C stocks and may result in net CO_2 removals from the atmosphere (Fig. 42.5). Biochar is a fine grained, C-enriched by-product which is generally produced during controlled pyrolysis of organic materials such as crop residues, wooden chips, feedstock's, litter, poultry and dairy manure, sewage sludge, etc., under controlled or limited oxygen supply (Sohi et al. 2010). Generally it is a slowly decomposed material compared to fresh plant residues and mineralized 10–100 times more slowly than uncharred biomass (Lehmann and Joseph 2015). Thus C added through biochar can be restored in soil over several decades. Results from recent experiment, which was done by El-Naggar et al. (2020), that application of different biochar produced from Amur silvergrass (*Miscanthus sacchariflorus*), rice straw, and umbrella tree wood (*Maesopsis eminii*) residues increased 77% and 44% in total carbon in sandy and sandy loam soils. Possible explanation might be due to its high carbon content and potential to store carbon in recalcitrant aromatic structure (El-Naggar et al. 2018a, b).

Addition of Bio-Energy Crops

Plant materials containing higher biomass with having high energy potential and grown mainly for production of bio-energy could be defined as bio-energy plants or crops. Broadly this is classified in two generations; first-generation (1G) included food crops, such as wheat, corn, sugarcane, sugar beet, etc., and second-generation (2G) included that crops which grown mainly for bio-fuel purpose, such as perennial grasses like Miscanthus (*Miscanthus giganteus*), switch grass (*Panicum virgatum*), and other bio-fuel producing plants (e.g., *Jatropha curcas*, *Pennisetum purpureum*, etc.). Harris et al. (2015) showed with a meta-analysis experiment that, conversion of arable land to perennial grasses could be able to increase 25.7% organic carbon in soil.

Priming Effect

Extra decomposition of native soil organic matter due to addition of fresh organic amendment into soil is called soil priming. It is influenced by several factors, such as exogenous carbon compound, climatic conditions, soil physical properties, soil microbial properties, etc. (Bastida et al. 2019). Positive effects of priming have been observed more in arid locations with low SOC contents over mesic sites with higher SOC contents might be due to nutrient limitations and presence of higher content of aerobic bacteria (Delgado-Baquerizo et al. 2017). Recent studies showed that, adaptation of conservation tillage with retaining crop residues in to soil can increase rate of C sequestration by lowering the priming effect in soil (Kan et al. 2020).

42.5.1.3 What Is Needed for Effective Arrangement of Soil Organic Carbon Research?

Some key points that are in need to sequester C and enhance soil productivity are given below;

- Knowledge on the functionality of soil system, such as activities of soil biota on improving soil structure need to be improved.
- Proper knowledge on SOC dynamics and its effects on soil health need improvement.
- Sampling strategies should be optimized on regional scale for potential use within a SOC accounting scheme.
- Random investigation on examination sites for keeping knowledge on ongoing conditions of experimented soil. Whether C is lost through erosion or built up of SOC by burying at depth.

- The “practice” of short-term versus long-term soil C sequestration should be more clearly defined. C pools that can equate to a permanent sequestration of C need to be clarified.

A collaboration and communication between the “science community” and the “practice sector,” facilitated by individuals that are knowledge brokers as defined by Bouma et al. (2011) is required along with “hard knowledge and social intelligence” for the future of SOC research.

42.5.2 Soil Management to Reduce CH_4 Emissions

Soil aeration, substrate availability, temperature, and addition of nitrogenous fertilizers are the key determinants of soil CH_4 fluxes (Segers 1998); therefore, proper management of soil can radically alter CH_4 fluxes. It was reported that, breaking down of organic compound due to microbial activities on anaerobic soils contributes more than one third (>200 Tg yr.$^{-1}$) of global methane emission (Ciais et al. 2014). Wetlands (177–284 Tg yr.$^{-1}$) and soil under rice cultivation (33–40 Tg yr.$^{-1}$) are the largest source of CH_4 emission while well aerated soil (< 30 Tg yr.$^{-1}$) acts as a sink for CH_4 from the atmosphere via CH_4 oxidation. Improve drainage and addition of organic amendments in rice soil could reduce CH_4 emission by 7.6 Tg yr.$^{-1}$ globally (Smith et al. 2008). Changes in N inputs, temperature, precipitation, and concentration of atmospheric CO_2, all are to affect net CH_4 fluxes from soils (van Groenigen et al. 2013).

42.5.3 Soil Management to Reduce N_2O Emissions

N_2O fluxes are directly related to N applied to the crop land and about 1% of the N input is directly emitted as N_2O (Bouwman et al. 2002). Therefore, better N management not only reduces N_2O emissions but also ameliorates other environmental problems, like nitrate pollution of ground and surface waters caused by excess reactive N in agro-ecosystems (Fig. 42.5). Arable soils give high crop productivity. Emission of N_2O from arable soil to atmosphere was also recorded higher (4.2 Tg of a global anthropogenic flux of 8.1 Tg N_2O-N yr.$^{-1}$) (Smith et al. 2008). Addition of ammonium fertilizer, nitrogen fixation from the atmosphere by legumes, nitrification, mineralization from soil organic matter, crop residue, or other inputs are oxidized to nitrite and then to nitrate in a series of reactions and that can also produce N_2O. However, recent evidence suggests that, N_2O emission can be reduced by addition of commercial additives such as nitrapyrin and dicyandiamide. These additives help to reduce nitrification rate by slowing down ammonium oxidation. Field experiments suggest that inhibitors can reduce N_2O fluxes by up to 40% in some soils (Akiyama et al. 2010). Nitrogen conservation can be achieved by adoption of the following strategies:

- Use of advanced statistical and quantitative modeling for optimum application rates of N that needs to crops.
- Modification on methods of fertilizer application. Applying fertilizer at variable rates across a field rather than broadcast on the soil surface; and.
- Time of fertilizer application needs to be verified. Applying fertilizer when crop need that most and can use it, such as several weeks after planting, or adding it earlier but release pattern is slow (use of slow release nitrogenous fertilizer).

42.5.4 Potentiality of World Soil for C Sequestration and Mitigation of GHGs Emission

Lal (2000) reported that well managed agricultural soil able to sequester C at the rate of 0.4–0.6 Pg C year^{-1}, while control in desertification has potential to sequester 0.2–0.6 Pg C year^{-1}. Therefore, the total potential of soil C sequestration may be 0.6–1.2 Pg C year^{-1} (excluding erosion and bio-fuel offset). Recently Zomer et al. (2017) reported that with rational management practices globally agricultural lands could sequester 0.90–1.85 Pg C year^{-1}, if the SOC content in the 0–30 cm depth layer of all available crop land increased from 0.27% to 0.54%. Maintaining this ratio would be capable to achieve 26–53% of the target of the "4p 1000 Initiative: Soils for Food Security and Climate." Thus, management of agricultural land is mandatory for achieving large global GHG reductions though how much is achievable will depend heavily on the implementation of management strategies in an effective way with socioeconomic conditions and policy constraints.

42.5.5 What Is Needed for Effective Implementation of Mitigation Practices?

GHGs mitigation practices in agricultural land are facing some challenges. Rates of individual land for implementation of mitigation practices are low, but adopting vast areas of land with engaging substantial number of these land owners and controlling them in proper way is a massive undertaking in itself. Therefore, it is mandatory to adopt several strategies for implementation of GHGs mitigation practices, which are as follows;

- *Regulation and taxation.*
  Reduction of GHGs at the farm scale by adopting direct regulatory measures is probably politically unfeasible and costly. On the other hand, developed countries like USA and Europe already implemented taxation on excess use of nitrogenous fertilizer which acts as an indirect tax that would reduce N_2O emissions.

- *Subsidies*.
  Subsidies for implementing GHG reducing practices are emerging as an alternative policy. For example, US Department of Agriculture has already included GHG mitigation program as a conservation goal (Louwagie et al. 2011).
- *Supply-chain initiatives*.
  Sustainability metrics including low GHG footprints are being targeted by major food distributors as a consumer marketing strategy by setting performance standards for contracted agricultural producers that includes the required field-scale monitoring of production practices and quantification of GHG emissions.
- *Cap and trade*.
  Cap and trade also known as emissions trading scheme or ETS is a market-based approach to controlling pollution by providing economic incentives for reducing the emissions of pollutants. Cap and trade programs are a flexible environmental regulation (Teeter and Sandberg 2017) that allows organizations and markets to decide how best to meet policy targets. Bayer and Aklin (2020) showed that European Union Emission Trading System successfully reduced CO_2 emission even though the prices for carbon were set at low prices.

42.6 Challenges and Opportunities in Indian Agriculture

In India, over 58% of rural households depends on agriculture as an option for their principal livelihood (FAO 2015). Agriculture and its allied sectors contribute ~17% to the gross domestic product and also provide about two-thirds of the employment in India. Thus; development of Indian economies along with employment generation and poverty eradication is directly linked with growth in the agriculture sector (Fig. 42.7) (Srivastava et al. 2016). Indian population increases with a growth rate of ~18% and is expected to reach up to 1.5 billion by 2050 (Ministry of Home Affairs 2011). After green revolution, the area under cereal cultivation has decreased from 38 Mha (1950–51) to 31 Mha (2003–04) but production increased more than

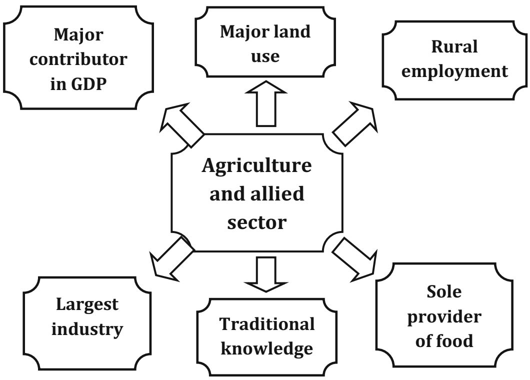

Fig. 42.7 Contribution of agriculture and allied sector in India

double from 15 MT (1950–51) to 38 MT (2003–04) leading to attain self-sufficiency in food production to meet the increasing demand of food in India. Different agricultural management practices based on green revolution led to substantial increase in food production but at the cost of environmental safeguard which necessitated a thorough scrutiny of those agricultural practices. It was reported that, the initial increase in crop productivity indirectly resulted in the global reduction of 161 Gt C emissions till 2005 with reduction in grain yield of rice and wheat in several regions (Vermeulen et al. 2012). This emission of C from agricultural land catalyzes global warming and other climatic phenomenon. Indian agriculture currently faces several challenges. These are as follows:

- Positive effects of green revolution in India in the form of instant increase in food production increased the use of external input-driven approach in agriculture which fawning the importance of internal regulation in the agro-ecosystem functioning, biological interactions, soil quality and its multi-functionality and environmental sustainability (Srivastava et al. 2016).
- Excessive inputs of agrochemicals increase availability of several free and reactive chemical species (like nitrate, phosphate, ammonia, chloride, heavy metal contents, etc.) in soil system (Singh 2001) which resulted in the increase in environmental pollution. This can be easily seen in several regions in India, particularly in Haryana and Punjab states.
- Agriculture consumes ~70% of global surface water for the purpose of irrigation and crop production. In India, the phenomenon of precipitation and water availability has become very uncertain due to recent climate change (Sarkar et al. 2017). Therefore, to meet the demand of water for growing of crops, India is fully dependent on supplemental irrigation such as canal and well irrigation. Flooded rice consumes 45% total fresh water which is two to third times higher than wheat and maize. India is the second largest producer of rice and wheat all over the world. Thus, India has become one of the largest users of ground water.
- In India indiscriminate use of agro chemicals for higher production of crops led to an alarming situation for the soil system. Organic matter plays a key role in long-term conservation of soil while its deterioration under conventional farming system declines soil quality (Sankar Ganesh et al. 2017). According to Sreenivas et al. 2016, carbon content in the top 1 m of Indian soils varies from 20 to 25 Gt C, which is equivalent to 4–8 g kg^{-1} SOC levels for most cultivable soils (Lal 2016). Nath et al. (2018) reported that, India contributes only 1.4–1.8% (of 1408 Gt) of the global SOC stock in the top 1 m. Indiscriminate use of chemical fertilizers enhancing acidification in tropical soil and further led to deterioration of soil quality and decreases soil productivity (Ganesh et al. 2017). Nutrient concentration and their availability in soil are also under threat due to injudicious application of chemical fertilizers. Thus, availability of nutrient which is necessary for crop production is a major challenge in the present agriculture system.

- The most susceptible group due to environmental degradation and who all are continuously facing the challenge of hunger, poverty, and further land degradation are the farmers (Lal 2016). Therefore, nowadays it is highly in need to shift farmer's interests towards productive agriculture for long-term sustainability of Indian agriculture.

It is predicted that, Central and South Asia may face a decrease in crop yield up to 30% due to change in weather and climate (Arora and Bhatt 2016). However, it is expected that climate-smart soil management with its inherent capacity to develop ecosystem resilience, resource conservative nature, and dependency on more natural measures can cope-up the severe damage of climate change. Therefore, it is necessary to develop effective policies that reduce the uncertainties of adaptive management practices and promote soil-based GHG mitigation.

Government should come forward and play a central role in promoting the use of climate-smart soil management technologies for betterment of agricultural activities of the farmers. Kishore et al. (2018) have made an attempt based on the six pillars of CSA (water smart, energy smart, nitrogen smart, crop smart, knowledge smart, and weather smart) to unfold the government policies between the year 2012 and 2017 towards the development of climate-smart agriculture in India. They stated that, 15% of average public expenditure on agriculture (including subsidy and investment) in India has been spent on CSA. Of the total government expenditure towards the development of climate-smart agriculture, 54% has been spent for nitrogen smart, 15% for weather smart, 11% for water smart, 11% for knowledge smart, 9% for crop smart, and rest 1% for energy smart agriculture. Different Central Government policies/programs with various components of climate-smart agriculture are given in Table 42.3 (Kishore et al. 2018).

42.7 Conclusion

Climate change results in greater uncertainty and risk among farmers and policymakers through its negative impacts on eco-functionality of natural resource base. The lion share of the success of climate-smart agriculture depends on climate-smart soil management strategy which is a smart approach for keeping soil healthy through enhanced carbon loading and thereby curbing greenhouse gas emission and improving crop production under changing climatic situations. Greater attentions should be given by different policy and research organizations towards management of soil under changing climate to meet the global pressure on food security. Right practices, policies, and investments can move the agricultural sector onto CSA pathways which will help to decrease food insecurity and poverty in short term and negative impacts of climate change over longer term.

Table 42.3 Central government policies/programs and their map of concordance with various components of climate-smart agriculture (Adopted from Avinash Kishore et al. 2018)

Mapping of policies with different components of climate-smart agriculture						
Government policy/program	Water smart intervention	Energy smart	Nitrogen smart	Crop smart	Knowledge smart	Weather smart
Prime minister agriculture irrigation plant (PMKSY)	Micro irrigation (drip and sprinkler)				Capacity building	
	Water conservation and harvesting					
	Irrigation infrastructure through MGNREGA					
National Mission for micro irrigation (NMMI)	Micro irrigation (2005–06 to 2013–14)					
National Mission for sustainable agriculture (NMSA)	On farm water management (2014–15)		Soil health card and management			
	Rainfed area development					
Rashtriya Krishi Vikash Yojana (RKVY)	Micro irrigation		Integrated nutrient management	Crop diversification and development		
National Food Security Mission (NFSM)	Natural resource management	Resource conservation machine	Integrated nutrient management		Farmers' training	
	Conservation agriculture					
	Micro irrigation					

National Mission for horticulture	Micro irrigation			Area rejuvenation		
Renewable power program		Establishment of solar pump				
National Mission on agriculture extension and technology (NMAET)		Farm mechanization			Training on improved agronomic practices	
Agriculture insurance						Pradhan Mantri Fasal Bima Yojana
Weather advisory						Agrometeorology

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