Chapter 12
Microbial Rejuvenation of Soils for Sustainable Agriculture

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Abstract Agriculture is actually facing reduced production, increasing costs, and increasing resistance of plant pathogens and other pests. The extensive usage of agrochemicals, monoculture, and soil pollution have deteriorated soil health. Poor management practices have altered the soil biology, deteriorated the soil structure, and reduced the soil organic matter content, calling for more sustainable management such as the use of microorganisms for rejuvenating degraded soils. Here we review the improvement of soil health with microorganisms with focus on carbon sequestration, nutrient cycling, degradation of contaminants, reduction of plant pathogens, and reduced usage of fertilizers.

Keywords Agroecosystem · Tillage · Irrigation · Soil health · Soil structure · Carbon sequestration · Monocultures · Xenobiotic compounds

12.1 Introduction

Agriculture, in a wide range, is an act of integration of definite agro-ecological elements and the production inputs for optimal crop yield and livestock production. The traditional act of practicing agriculture confronts several issues like abridged production, amplified costs, deteriorated soil health, etc. Furthermore, the agricultural practices of monocultures on the same land have serious ill effects like depletion of top soil, lowering of groundwater quality, degradation of soil vitality, and

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reduction in the population of beneficial microbes which make the crops more vulnerable to the attack of various pathogens and parasites. The ever-increasing usage of pesticides and fertilizers along with the energy demands for ploughing to ventilate soils and the accelerating costs of irrigation are much-concerned issues (Singh et al. 2011, 2019a; Sharma et al. 2020a, b).

Moreover, the existing human practices of unrestrained application of chemicals escalated usage of non-renewable and conventional energy sources and unchecked generation of a vast array of left-over produce in every sort of industrial process has gallantly crumbled the environmental sustainability. Thus, the world now faces a galactic need as well as responsibility meant for the adoption of tenable measures for cleaner production and also the involvement of green technologies for preserving the ecology of this green planet for the coming generations (Akinsemolu 2018; Kumar et al. 2020).

Although, the green revolution has proved to be an act of paramount success of human efforts which has resulted in attaining worldwide food security especially in some developing countries like India which has travelled far enough to become food surplus from food deficient countries but the gradual and shocking rise in human population is again becoming a hindrance in the global food security thus sparking the need for another green revolution to endure the burden levied by increasing population (Vasil 1998; Leisinger 1999; Rani et al. 2019; Singh et al. 2021). Chemical fertilizers are usually recommended for overcoming the deficiencies of different nutrients but the perpetual involvement of such fertilizers for yield improvement is attaining saturation beyond which there is no further enhancement in the crop yields.

Thus, it has become limpid clear that the prevailing agricultural methods are not potent enough to nurture the production base and a healthy plant-soil system for a longer time. This promiscuous and lavish employment of chemical fertilizers has become a seedbed for several environmental and health-related hazards thus piquing the need for the development of potent alternatives that can warrant competitive yields along with the protection of soil health. Such an approach to farming frequently appertains as sustainable agriculture which necessitates the environment-friendly agricultural practices that are meant for upholding the enduring ecological balance of the soil ecosystem. In this context, the use of microbial inoculants represents an eco-friendly substitute for mineral fertilizers (Khan et al. 2007; Sharma et al. 2021).

The microorganisms of agricultural importance are a viable option for the environment-friendly management and regulation of the efficiency and the availability of nutrients to plants; thereby they enhance soil fertility by ameliorating the soil biodiversity and nutrient availability (Mahawar and Prasanna 2018). Microorganisms are tremendously expanded by their roles in various environmental processes (Mehta et al. 2019; Singh et al. 2019b; Rahman et al. 2019; Kapoor et al. 2020). Furthermore, these are crucial agents in several cleaner technologies and green processes which range from biogeochemical cycling to several industrial production processes. Thus, the judicial use of microorganisms can play a major role in sustainable development (Kuhad 2012).

Biopesticides and biofertilizers are formulations comprising of effective microorganisms that improve plant growth in many different ways as compared to synthetic fertilizers and consequently help in improving crop productivity by preserving the sustainability of the environment. The rhizospheric soils also encompass a distinctive array of efficacious microbes with salutary effects on the overall productivity of the crops. The cyanobacteria and the plant growth-promoting rhizobacteria are among the various dwellers of the rhizospheric soil and produce various bioactive substances that are responsible for plant growth promotion and protection against various pathogens which makes them effective agents for agriculture improvement and environment sustainability (Singh et al. 2011). The soil biodiversity and the interactions of different organisms in soil have experienced rigorous changes under the green revolution technology. The major downside of the green revolution technology appears to be the loss of functional diversity of the soil which has significantly disrupted the efficiency of the ecosystem (Srivastava et al. 2016); thus, also deteriorated the soil health significantly.

Soil health is the capacity of soil to function as a vital living system, within the ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. According to Doran and Parkin (1994), soil quality is "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". Soil health is always related to the holistic management of the soil whereas soil quality is always described concerning the constituent parts of the soil *i.e*., physical, chemical, and biological parts of the soil. However, in this chapter both the terms are used in the same context. An important parameter for the determination of soil characteristics is the buffering capacity of the soil. The attribute of maintaining its productivity, despite facing several stresses like fluctuations in water availability, various kinds of soil disturbances including tillage, or different sorts of imbalances like outbreaks of pests is provided by the effect of buffering (Sherwood and Uphoff 2000).

The complexity of the soil systems is an undeniable fact. Soil structure is continuously modified by the soil microbes by aggregating both organic as well as mineral components via producing extracellular compounds which are endowed with adhesive properties. There is a consorted change pronounced in the structure of the soil as well as the topology of the network of pores which makes the microbial habitat and that affect the water accessibility and its distribution, gases and substrate delivery to organisms and also removal of the products of metabolism from their vicinity. Such kind of activities of microbes is strongly administered by the availability of organic carbon (Kibblewhite et al. 2008). Thus, soil health comprehends the living as well as the dynamic nature of the soil which distinguishes it from the soil quality.

The main focus of soil is on the capacity of the soil to meet distinct human requirements such as the growth of any specific crop, whereas soil health is mainly focused on the soil's sustained capacity to withstand the growth of the plants along with the maintenance of its functions (Bünemann et al. 2018). People alter natural systems, however, because the existing maximum biological productivity is either insufficient or undesirable. Some soils are quite accommodating to human interventions while others have a low tolerance.

The organic matter content of healthy soil should be high as the organic matter acts as a pool of nutrients as well as moisture, and thus, maintain a vast diversity of organisms to flourish in the soil environment. Thus, it is necessary to add organic amendments regularly for maintenance as well as enhancement of the soil organic matter content to improve soil health (Turmel et al. 2015).

However, several human practices like, addition of municipal solid wastes impairs the soil quality as it contains heavy metals like lead, cadmium *etc*., in a very high concentration, which also leads to the contamination of the food chain. Thus, extreme addition of metals causes metal pollution which may affect the soil quality (Smith 2009). The soil microbial biomass is an important parameter for assessing soil health and is very sensitive to heavy metal concentrations in soil and water (Ouni et al. 2013). Soil pollution also significantly affects soil microbial biomass which disturbs various microbial processes in the soil; thus, deteriorates soil health (Romero-Freire et al. 2016). Agricultural practices and land use patterns also vigorously affect soil health. The practice of crop rotation favours the natural process of nutrient replenishment (especially nitrogen) and also pulverizes the possibilities of any kind of comprehensive pest burst, thus permits benefit to the farm system from the available biological diversity (Table 12.1).

12.2 Constituents of Healthy Soils

There are different vantage points for the assessment of soil health. The general perspective of health assessment is an evaluation by productivity which could range from biomass production to productivity indices corresponding to elementary properties of soil. Earlier studies about the soil-fitness were based only on yield increment targeting the profit outlook. As the various aspects of soil conditions are being realized, the quality of soil is gaining wider and worldwide attention. Soil is the bedrock of water security, food security, biodiversity protection, and climate change mitigation (McBratney et al. 2014). The high-quality soil also means a greatly fruitful soil with very small levels of soil degradation along with the high capability to resist extreme weather conditions and a diminished loss of nutrients (Karlen et al. 2013).

The different ways of classifying soil health usually involve multiple facets concerned with physical as well as chemical properties of the soil including some biological indicators. According to the Food and Agriculture Organization of the United Nations; soil health is defined as the “soil’s capability of functioning as a living structure, with the ecosystem and the land-use boundaries, to endure the productivity of the animals and the plants, preserving or improving the quality of air and water, and encouraging the health of plants as well as animals. The occurrence of a diverse community of microbes in the healthy soils check plant disease, controls insects and weeds and also form symbiotic associations with the roots of the

Table 12.1 Factors affecting soil properties and possible remedies for soil health improvement

Factors	Consequences	Remedies	Mechanisms	Remarks	References
Metal contamination and acidification	Reduced growth of lettuce plant	Alkaline amendments	Improvement in the enzymatic activities, and bacterial community structures in the soils	The amendments led to an enhancement in the levels of Proteobacteria and Gemmatimonadetes in the soil which are vital for phosphate dissolution, microbial nitrogen metabolism, and soil respiration	Lu et al. (2020b)
Tillage	Soil disturbance and depletion of soil organic carbon pools	No-tillage agriculture coupled with a cover crop	Improvement in soil organic carbon, total nitrogen, available phosphorus, exchangeable K-Mg, cation-exchange capacity, bulk density, soil penetration resistance, and substrate-induced respiration	The Z-score formula, a formula to calculate the value of certain variables that we observe with a specific treatment factor and compare it with the average value of certain variables in all treatments, for soil organic carbon, several soil characteristics, crop productivity, and biomass input, ensured the employment of the combination of no-till with cover crops as a tool to improve soil-health	Wulanningtyas et al. (2021)
Continuous cropping	Decline in soil organic carbon	Biochar addition	Increase in soil organic carbon, nitrogen pool, decline in bulk density of soil, and increase in microbial abundance	Biochar addition is a beneficial tool to improve soil health for ensuring food production in agricultural land facing degradation and climate change impacts	Lu et al. (2020a)
Reduced soil organic carbon	Reduced barley production	Organic amendment	Improvement in fertility status of soil, enhancement in soil enzymatic activities and improvement in physical properties of soil	Use of organic wastes is an efficient tool for improving health of nutrient-poor soils of the arid and semi-arid regions	Lal et al. (2020)

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Table 12.1 (continued)

Factors	Consequences	Remedies	Mechanisms	Remarks	References
Management practices	Deteriorated soil health	Higher crop diversity, fewer tillage operations, and higher number of organic amendments	Higher levels of aggregate stability, protein, active carbon, respiration, and organic matter	Soil management is the key for soil health, management practices comprising of crop diversity, zero tillage, and application of organic amendments promote soil health	Williams et al. (2020)
	Reduced plant productivity	Rice husk biochar application	Improved soil pH and carbon content	Biochar application is an effective tool for alpine meadow restoration	Rafiq et al. (2020)
	Deteriorated soil health	Wheat-sorghum rotation as cover crops	Change in microbial community structure and enzymatic activities	Cover crops increase the total microbial community size, fungal abundance, and enzyme activities associated with carbon and nutrient cycling	Thapa et al. (2021)
	Deteriorated soil health	Organic amendments	Overall improvement in the soil quality index by the interaction of soil properties	Addition of organic fertilizers improves soil quality and plant yield as compared to chemical fertilizer	Li et al. (2020)
Heavy metal contamination	Reduced plant productivity	Biochar application	Increase in pH, organic matter content, and available phosphorus in soil and reduced bioavailable vanadium	Biochar application is a cost-effective and ecofriendly amendment for both soil quality improvement and the vanadium contaminated soil remediation	Yu et al. (2020)
	Declined soil health	Compost application	Slow-release of nutrients and thus favoring long term soil fertility and immobilization of heavy metals	The soil health improves considerably even at the lowest compost application rate	Alburquerque et al. (2011)

plants; recycle vital plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity thus eventually enhance the crop production" (FAO 2008). Furthermore, healthy soils generate healthy produce that sequentially nourishes humans and animals (FAO 2015).

The quality of soil cannot be determined directly, but it refers to evaluating the physical, chemical as well as biological properties of the soil (De Paul and Lal 2016). The agricultural point of view has mainly long focused purely on the physical as well as chemical properties of the soil whereas the innate biological constituents of the soil which contribute to the overall soil health were fiercely neglected. The soil mass present in $1 m^3$ of soil lies in the range of 1200–1700 kg of soil which contains around 2.3–2.6% of soil's total carbon in the form of microbial biomass (Haney et al. 2018).

The steady-state conditions of the soil are usually utilized by the soil researchers as an estimate of the microbial activity of the soil (*i.e.*, constant water, temperature, and oxygen content). This was the possible initial methodology for laboratories; nevertheless, the drying/rewetting cycle induced by the rainfall and events of the irrigation leads to the creation of a highly dynamic mechanism of nutrient cycling which is driven by microbes in the agricultural fields (Haney and Haney 2010). The researchers recognized CO_2 respiration as an indicator of soil fertility around 100 years ago (Gainey 1919; Lebedjantzev 1924). The microbial biomass has an important role to play in decomposing the organic matter as well as the cycling of nutrients, and thus, is extremely allied to the vigorous pools of probable carbon and nitrogen mineralization. The organic compounds from the soil organic matter are usually oxidized by the microbial population along with the release of CO_2 (Haney et al. 2018).

The concentration of soil organic carbon is usually deliberated as a representation of the soil quality as it optimally symbolizes the dynamics of the soil biota and also plays a crucial role in the fertility of the soil, water availability, and stability of aggregates in the croplands. There are various other soil attributes like bulk density, soil depth, respiration rate, pH, electrical conductivity which help to understand the soil processes thus incorporating evolving concerns on the assessment of the soil quality (De Paul and Lal 2016). However, it is also anticipated that the inputs of various elements like P, C, K, Mg, and Ca are found to be higher in low input or conventional and organic agricultural systems which are considered as a good sign of soil health.

Soil pH along with microbial biomass is also found to be somewhat higher in the soils which are organically managed. Such soils contain a vast diversity of bacteria, fungi, nematodes, earthworms, and arthropods as compared to other soils. Highly assorted ecosystems with various taxa that form a multifarious food web having several trophic levels are usually deliberated as healthy and thriving ecosystems. Consequently, the taxonomic and functional variety indices are frequently used as indicators of soil health status. The soils which are regularly cultivated possess a lower microbial diversity as possessed by them as the natural habitats. Thus, organically managed healthy soils appear to be healthier as well as natural compared to the other management strategies (van Bruggen et al. 2015).

There are several factors in organic farming like disparate crop rotation, utilization of carbon-based alterations which contribute to the overall soil fertility. Such exercises significantly upsurge the biologically accessible soil organic matter along with an increase in the number of beneficial soil microbe as well as invertebrate activities which further improves the physical properties of the soil, condense the disease potential, and ultimately escalate the plant health. Several studies have also proved that the fruits and vegetables grown in healthier and organic soils comprehend a greater level of health stimulating phytochemicals (Reeve et al. 2016). Thus, various unhidden aspects of soil fertility strongly affect the produce, plant, and animal health along with an ultimate effect on human health.

12.3 Importance of Soil Health

Soil health has an important role to play in agricultural production, quality of food, environmental resiliency, and sustainable management of the ecosystem. The recent concerns on food policy have progressively concentrated more on the notion of soil health which holistically measures the productivity of the soil along with its resilience and sustainability. The findings of various disciplines of science like agronomy, soil science, ecology, and plant biology have made it quite clear that soil has a great impact on food security and nutrition. In light of these findings, the year 2015 was declared as the international year of soils by Food and Agriculture Organization. The benefits derived from soils of superior health can be easily categorized into ecological/environmental benefits and agronomic benefits. The agronomic benefits of healthy soils mainly correspond to the elevated yields, better pest management, reduced usage of fertilizers, and less necessary irrigation practices; whereas the ecological benefits are mainly concerned with better environmental management principles. The main benefits derived are reduced rate of erosion, flood control, better carbon sequestration, cleaner water due to less flow of nitrates, and enhanced biodiversity (Stevens 2018). Thus, the importance of soil health can never be undermined.

The fundamental effect of the soils on human health is very well-acknowledged. There are several positive effects of soils on human health such as the supplement of vital nutrients for the production of nutritious food for the human diet and it also acts as a basis of various antibiotics (Brevik et al. 2018). Several nutrients having importance to human health find their origin in the soil. As plants grow in the soil these nutrients are absorbed by the plants and then these are passed on to human beings feeding on that plant material (Brevik et al. 2017). Plant fibers are a great source of clothing, various fibers like flax, cotton, and hemp are important sources of fibers for making clothes. Such plants also find optimal growth conditions in healthy soils.

Another important aspect related to healthy soils is the practice of water conservation. The practices that promote soil aggregation encourage many properties of the soil, comprising water infiltration as well as retention. The increase in the organic matter content of the soil has a direct effect on the water-holding capacity of the soil. An increase in soil organic matter by only one percentage point amplifies the water-holding capacity of soil beyond 252,556 Litre/hectare (Cano et al. 2018). The rate of water infiltration is significantly higher in healthy soils. Healthy soils can upsurge the water infiltration as well as storage from precipitation. It is of ample importance as conservation of water meant for irrigation purposes is strongly favored along with an increase in crop productivity and a decline in soil erosion (Lehman et al. 2015).

12.4 Indicators of Soil Health

The quality of soil is one of the three constituents of environmental quality in addition to the air and the water quality (Andrews et al. 2002). Air and water quality are usually defined largely by the extent of pollution they suffer that have various direct impacts on human as well as animal health, and also on natural ecosystems. Conversely, the definition of soil quality cannot just be inferred from the extent of pollution in the soil but is often defined from a broad range of parameters (Bünemann et al. 2018) (Fig. 12.1).

The site-specificity, as well as the complexity of the underground ecosystem along with the associations among soil-based ecosystem services and the soil functions, should also be reflected while defining soil health. The quality of soil is indeed much complex as compared to the water and air quality, not because soil constituents may be either of different states, but also because soils can be used for a larger variety of purposes (Nortcliff 2002). The changes in quality of soil can be evaluated by assessing suitable indicators and the obtained values can further be compared

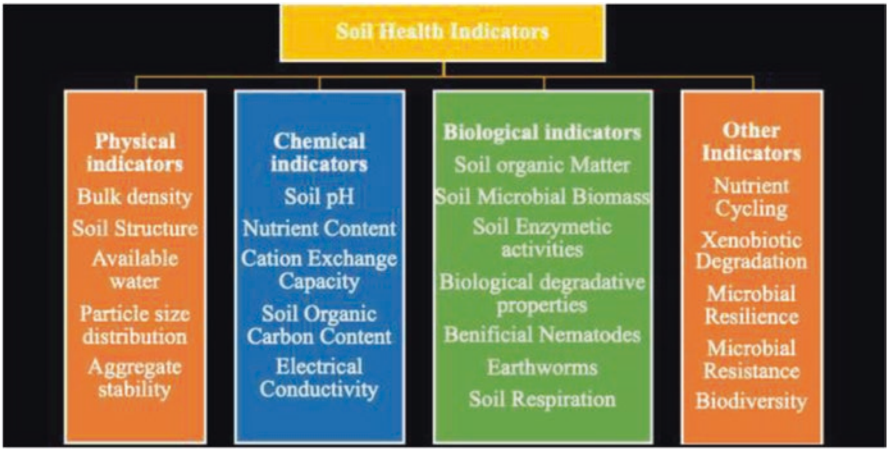

Fig. 12.1 Indicators governing soil health

with the expected values which are usually threshold levels or critical limits at different intervals of time (Arshad and Martin 2002).

12.4.1 Essential Characteristics of Soil Health Indicators

The indicators of soil health are referred to as assessable characteristics of the soil influencing the soil's capacity of conveying ecosystem services. The attributes of soil showing the most sensitivity towards the management is often considered desirable indicators. They are found to be responsive towards the management of agriculture thus reflecting changes in the functional properties of the soil and are finding an increased usage in the assessment of the current condition of the soil health (Takoutsing et al. 2016).

Presently, there is no unanimity among the scientific community concerning the finest indicators to be dignified in the health assessment of soil through diverse agroecosystems. Preferably, the indicators of soil health must be much sensitive enough for the detection of alterations in the soil ecosystems and thus signify functions appropriate to the agricultural systems and the soil management (Lehman et al. 2015). These indicators need to be penetrating towards the alterations which appear due to the management practices of the soil and should cover an extensive range of environments along with the integration of physical, chemical as well as biological properties (Doran et al. 2002).

Moreover, these indicators need to be economical, reproducible, and accessible to the producers through various laboratories and offered online to community shareholders for the collection of meta-data and supervision in practices of management as well as the development of databases, online repositories, and tools for future researchers (Cano et al. 2018; Anamika et al. 2019). The suitable methods for assessing soil health are still under controversy as a single indicator cannot comprehend all the facets of soil health and the measurement of all the possible indicators is not feasible (Takoutsing et al. 2016). There are several soil indicators and some of them can be easily observed by touching and viewing whereas others require various specialized apparatus as well as analytical skills. This is an undeniable fact that determining the various features of soil health can be a hellacious job even in the farming systems having technological advances at the peak.

12.4.2 Soil Health Parameters

Although there are myriad ways of systemizing soil health measures, a common framework is often shared by different authors. Soil health can easily be construed into three major constituents: physical, chemical, and biological characteristics. There is an existence of various possible attributes as well as indicators governing soil health within these three basic components (Stevens 2018). The chemical properties used for the assessment of soil health are often found to be very limited due to the heavy charges of sample analysis. Moreover, the trustworthy, as well as the precise methods for assessment, are still not available. There is also a great scarcity of various monitoring initiatives in this field along with the inadequacy of land management in a sustainable way (Shepherd et al. 2015).

12.4.2.1 Physical Parameters

There are various kinds of physical parameters which have been best argued for being used as soil health indicators like, bulk density, soil structure, available water, particle size distribution, aggregate stability etc. (Rabot et al. 2018). The soil organic carbon content can also be mapped by various high-resolution mapping devices such as remote sensing devices along with progressive geostatistical methods (Rinot et al. 2018). The soils of sound health are found to have a high organic matter which permits the growth of a great variety of soil organisms and also acts as a pool of soil nutrients along with adequate moisture. The regular addition of organic amendments is essential to upsurge or sustain the organic matter content of the soil and thus it subsidizes the soil health (FAO 2011). In common, the quality of soil is indistinguishably associated with the dynamics of soil organic matter and soil carbon, which have a direct influence on the physical, chemical, and biological function of the soil.

The soil organic matter leads to the stabilization of the aggregates, helps in the prevention of erosion, upturns the water-holding capacity of the soil, and also encourages slow-release of nutrients (Karlen et al. 1990). In general, the soil's physical possessions provide information related to water and air movement through soil, as well as conditions affecting germination, root growth, and erosion. For instance, the soil physical property of aggregate stability is a relative measure of confrontation of soil aggregates to exterior energy like heavy rainfall and cultivation, which is particularly governed by the soil structure. The soil structure represents an important health indicator as it also governs the accretion of organic carbon, penetration capability, movement as well as storage of water, and root and microbial activities. Furthermore, it also measures the soil resistance towards erosion as well as other management-induced changes (Allen et al. 2011).

The soil structure also governs the pore size of the soil systems which is further strongly linked to the soil physical quality as it has a direct influence on the soil physical indices comprising soil aeration capacity, plant available water capacity, and relative field capacity (Reynolds et al. 2009). The speed at which water comes into the soil surface and travels through soil depth is acknowledged as soil water infiltration. The water infiltration rate has also been accepted as a potent indicator of soil health owing to its ability to alter with soil use, management, and time (Arias et al. 2005; O'Farrell et al. 2010).

The soil bulk density, which happens to be a measure of soil compactness is also a useful indicator of soil health owing to its negative correlation with soil organic matter and soil organic carbon content (Weil and Magdoff 2004). Several other physical parameters like rooting depth and soil surface cover have also been found to affect the important ecological processes happening in the soil systems, thereby, have also been accepted as important soil health indicators (Allen et al. 2011).

12.4.2.2 Chemical Parameters

The chemical indicators like soil organic carbon content, nitrogen content, and pH have also found wide applications in the assessment of soil health (Rabot et al. 2018). Of them, the pH of soil along with several other factors like the salt concentration in soils, nutrient retention capacity, soil toxicity, and oxygen accessibility to plant roots also represent important chemical parameters governing soil health (Srivastava et al. 2020). The pH of soil systems is largely a function of soil parent material, time of weathering, vegetation, and climate, and is deliberated among the leading chemical indicators of soil health. The soil pH indicates the changing patterns of soil's biological as well as chemical functions comprising acidification, salinization, crop performance, nutrient obtainability, and cycling and biological activity (Dalal and Moloney 2000).

Another important chemical parameter is soil electrical conductivity, which is a measure of soil salt concentration, is deliberated an effortlessly measurable and trustworthy indicator of soil health owing to its ability to notify soil biological quality in response to crop management practices (Arnold et al. 2005; Gil et al. 2009). In addition to it, the cation exchange capacity governs the soil health owing to its traits of retaining the major cationic nutrients, like Ca, Mg, and K, coupled with the arrest of potentially toxic cations like Al and Mn. Furthermore, it also determines the soil's inherent capability of retaining toxic pesticidal particles and other chemicals. A lower value of soil cation exchange capacity denotes the augmented leaching of base cations in response to high and intense rainfall events (Allen et al. 2011). The accessibility of nutrients in the soil to the plant systems is also an imperative chemical indicator of soil health as the quantification of extractable nutrients gives a clear sign of a soil's aptitude to assist plant growth; along with a concomitant identification of the threshold values for environmental hazard assessment (Dalal and Moloney 2000).

12.4.2.3 Biological Parameters

The microbial section of soil signifies only 0.1–0.3% of the total volume of the soil, and yet is indispensable to the global soil quality, assisting 90% of the soil ecosystem occupations (Muñoz-Rojas 2018). The criteria for being useful indicators for soil quality assessment are also fulfilled by soil organisms and other biotic parameters (e.g., diversity, abundance, community stability, or food web structure). The organisms inhabiting the soil ecosystem react sensitively towards the climate and practices of land management. They are finely associated with beneficial and healthy soil and various ecosystem functions comprising decomposition and cycling of nutrients, water storage, and suppression of pathogenic and deleterious organisms along with detoxification of toxic compounds.

The richness and variety of soil organisms are found to be well allied with many constructive soil functions (Doran and Zeiss 2000). The largeness of the waves in microbial thicknesses, their occurrence, and the time needed to return to initial conditions before an organic amendment may be used as indicators for soil health. Soils with higher microbial diversity and variety are found to be more suppressive towards the pathogens. Thus, microbial resilience and resistance can serve as essential indicators of healthy soil (van Bruggen et al. 2015).

Major attribute defining soil fertility is soil basal respiration of microbial biomass (Niemeyer et al. 2012) which also serves as an indicator of the soil health or quality (ISO 2002). There are pronounced changes in the soil in response to any alteration in the soil affecting its quality (Romero-Freire et al. 2016). The microorganisms of the soil underneath stress can be metabolically less operative as they need more energy to invest for the maintenance of cell function, which results in an enhanced CO_2 carbon release per unit of the microbial biomass, this ratio is called a microbial metabolic quotient (qCO_2) (Niemeyer et al. 2012). The physical properties of the soil are also affected by microorganisms. Microbial maintenance of soil structure is done by producing various extracellular polysaccharides and other compounds or cellular debris which leads to the stabilization of soil aggregates by their functioning as cementing agents. Thus, the infiltration rate, erodibility, crusting, water holding capacity, and susceptibility to compaction are strongly affected. Therefore, indicators of soil health can be spotted by observing reactions of the microbial community of soil towards the application of diverse stress factors at numerous intensities.

The extent of a particular response and time required to come back to the same pre-stress situations can assist as measures of soil health (Gil and Gil 2011). Various members of soil fauna like nematodes, earthworms, collembolan, and predatory mites were also proposed as possible indicators of soil health whereas bacteria-feeding or predatory nematodes, soil algae, and basidiomycete fungi possibly will act as indicators defining soil facing industrial pollution (van Bruggen and Semenov 2000).

Nematodes are other members of soil fauna that can be easily traced in several marines, freshwater as well as terrestrial environments. They inhabit numerous trophic groups and fulfil significant roles in various ecosystem processes, and also respond quickly to environmental disturbances. These are habitually used as indicators of disturbances in various ecosystems that are induced by pollutants. Therefore, nematodes are also utilized as pointers of disturbances prompted by diverse agricultural practices (Du Preez et al. 2018).

Soil enzymes have also established much engrossment as long-standing biological indicators of soil health because of the correlation of enzyme activity levels to the organic matter, microbial biomass and soil physical properties, and microbial biomass. In addition to it, the enzymatic assays prove to be economical as well as easy to operate. Enzyme assays meant for the assessment of various nutrient transformations including N, P, C, and S cycles have been successfully developed.

Moreover, the changes occurring in soil health over a very little period of 1–2 years can be successfully measured by enzyme activities (Bandick and Dick 1999). Various enzymes, for instance, ammonia monooxygenase, nitrate reductase, urease, alkaline phosphatase, arylsulfatase, glucosidase, and hydrolysis of fluorescein diacetate (Dose et al. 2015) and dehydrogenase activity can be used as enzymatic indicators whereas β-glucosaminidase, β-glucosidase, arylsulfatase, and acid phosphomonoesterase are commonly assayed as indices of N, C, S, and P cycling, respectively (Acosta-Martinez et al. 2018).

Dehydrogenase is one of the important soil enzymes meant for the assessment of biological activities present in the soil. The dehydrogenase activity of the soil is a measure of total oxidative metabolic events of soil microbes; hence it is deliberated as a good indicator (Gu et al. 2009). The hydrolysis of fluorescein diacetate is used as another degree of quantifying total microbial activity because it can be easily hydrolyzed by both exoenzymes as well as membrane-bound enzymes (Schnurer and Rosswall 1982). It is often used for quantifying the amount of fungal and bacterial population positioned on the acetyl esterases in the alive protist cells (Dotaniya et al. 2019).

Due to increased human intervention and other biological processes, the quantity of xenobiotic compounds is steadily increasing in the soil. The degradation of xenobiotic compounds has also been proposed as an indicator of healthy ecosystems. The degradation of xenobiotic compounds is lower in soils facing heavy metal contamination (Kools et al. 2005).

12.5 Factors Affecting Soil Properties

The process of soil genesis or factors relating to soil formation is not the sole element affecting soil health. Soil health is also affected by the use and management practices of the soil (Moebius-Clune 2016) (Table 12.1). There is a significant decline in productivity with time which is further escorted by increasing requirements of fertilizers for attaining the desired levels of production (Dotaniya et al. 2013). Intending to assess soil degradation due to various anthropogenic activities, an appropriate understanding of various soil biological and physicochemical variables is very crucial (Tripathi et al. 2016). The community of farmers is often deceived with the myth of a proportionate hike in crop yields with the application of pesticides and fertilizers in huge amounts, which further deteriorates the biological quality of the soil.

The rate of decline of soil organic matter lessens the transformation rate of the nutrients as well as the accessibility of plant nutrients from the soil. In the case of sandy soils, the loss of nitrogen-containing fertilizers has been up surged due to the volatilization and leaching thus there is a requirement for a higher dose of nitrogen-containing fertilizers (Dotaniya et al. 2019). The pool of soil organic carbon is largely disturbed by agricultural practices which is a source of various greenhouse gases with great potential. Thus, the quality of soil is much degraded by the loss of soil organic carbon thereby laying more pressure on the sustainable production of crops and maintaining food security (Lal 2007). The over-application of fertilizers is found to be problematic as it leads to the accumulation of the fertilizers in the fields and their absorption is not permitted by the physiological mechanisms of the plants.

The key drivers behind the processes of nutrient transformations are microbes which mineralize the nutrients, thus promoting plant growth. The transformation and mineralization are conveyed by various microbial enzymes, that can either be endogenous enzymes or extracellular enzymes of microbes (Dotaniya et al. 2017). These enzymes are together called soil enzymes which are dynamic for sustaining fertility as well as the health of the soil along with the protection of the environment by the degradation of pollutants (Stirling et al. 2017). Thus, the activities of enzymes are well reflected in the respiration as well as the diversity of microbes. So, a low microbial count and lower enzymatic activity denote poor soil health. Sandy soils possess a lower microbial diversity and low population density. Although sandy soils get more aeration than clay soils, however the organic matter content of such soils is much low which restricts the growth of microbes (Dotaniya et al. 2019).

Likewise, the soils receiving much chemical treatment are also degraded easily and have poor soil fertility, and thus, abridge their potential of crop production (Dotaniya et al. 2016). The extent of global pesticide usage was 3.75 million Megagram in the year 2000 and it is further estimated to upsurge to 15.6 million Megagram by the year 2020 and up to 25.1 million Megagram by the year 2050 (Tilman et al. 2001). The technology of the green revolution has brought an adverse change in the biodiversity of soil and its interactions as well. The loss of functional biodiversity mediated by the green revolution has led to the destruction of the ecosystem's efficiency. The perpetual use of monoculture and automation, as well as enhanced usage of xenobiotic pesticides, has supposedly abridged the biodiversity of soil at each taxonomic level (Srivastava et al. 2016). There is a strong and dynamic effect of agricultural practices on soil health.

The process of crop rotation naturally replenishes the soil nutrients and maintains the biological diversity of the soil, and thus, protects the soil from pest outbreaks (Livingston et al. 2015). The traditional methods of soil management by rotating crops between nitrogen-fixing and nitrogen-leaching microbial species can solve this problem. Furthermore, tillage is another parameter and a dynamic managing judgment for farmers. The agricultural practices of no-tillage or low tillage can increase the organic matter content of the soil and lessen the erosion, but it can also promote the enlarged growth of weeds along with soil compaction.

Irrigation also plays a dynamic role in maintaining soil health. Soil properties are also influenced by irrigation patterns. The recent advancements of precise irrigation have permitted farmers the effective usage of water (Taylor and Zilberman 2017). Additionally, soil pollution is largely responsible for the reduction of microbial biomass of soil thus interfere with the capacity of performing key ecological functions. The presence of metals and metalloids is becoming an issue of environmental concern as these are not degraded and can accrue in the soils and sediment (van Gestel 2008). The increased anthropogenic activities have made the readiness of different metals like Pb, As, Cu, or Zn to the soil which are common pollutants of soil with a grave potential of degrading soil's ecosystems, and thus deteriorating soil fertility (Burgos et al. 2008). The presence of contaminant elements in the soils can ominously hinder the bacterial ability of decomposing complex substrates.

Furter, quick expansion of nanotechnology has augmented the usage of silver nanoparticles as antimicrobial additives in plastics, paints, washing machine liners, detergents, textiles, and food supplements (Impellitteri et al. 2009). They are progressively entering the environment, followed by their escalated production and usage, where the soil is anticipated to be the foremost sink (Gottschalk et al. 2013). Consequently, the silver nanoparticles may profoundly influence the soil ecosystem because of their great reactivity (Anjum et al. 2013). They have also been acknowledged for their inhibitory consequences on plant growth by causing discrepancies in the community composition of microbes, and further reducing the enzymatic activity of the soil. In addition, there is an enlarged accrual of silver in the plant tissues along with augmented antioxidant enzyme activity (Cao et al. 2017).

Human activities are also largely responsible for deeply modifying the soils and potentially worsening the soil features. Some of these activities are extremely alarming for example, during the infrastructure and the building construction. Others are less perceptible but are similarly as treacherous as regarding pedodiversity preservation (Lo Papa et al. 2011) and the protection of various environmental resources, concerning the formation of soil after the entombment of the wastes from numerous origins and nature. The creation of such new soils is always problematic (Lo Papa et al. 2018).

12.6 Soil Biology

The tiny sheet of earth's crust serving as the natural standard for growth as well as the development of plants is called soil. It is a natural body that consists of several layers called soil horizons. These horizons are different layers of mineral components of different thicknesses, which diverge from their native constituents in several ways. Thus, soil serves as a natural medium for growth, multiplication, and death for several life forms. There is a vast array of microorganisms that are present in the soil and are often designated as "black box" (Paul and Clark 1989). There is a tight association between soil microorganisms and the particles of soil. The conditions at the levels of microhabitats are not consistent and may keep on changing even at very small distances and such conditions strongly govern the activities of microorganisms present in the soil (Wieland et al. 2001). The microbial part of the soil is attracting much attention as the fertility of the soil is also governed by the quantitative as well as qualitative aspects of microflora inhabiting the soil. (Giri et al. 2005). The general classification divides microorganisms into five main taxonomic classes: Algae, Eubacteria, Fungi, Protists, and Viruses.

When the complexity level is taken into account eukaryotes are designated as more complex cells which further include Protists, Fungi, and Algae whereas prokaryotes are titled as structures with a lesser cellular complexity constituting Eubacteria and Archaebacteria (Bakshi and Varma 2011). There is great variation in the soil organisms and the discrepancy is observed from a few per hectare to countless per gram of soil. The supply of food, temperature, moisture, the soil reaction as well as the physical conditions of the soil strongly governs the population density of the biological part of the soil. The bacterial population is found to be dominating in the neutral soils whereas fungi dominate in the acidic soils and soils with high organic matter content. The moist and shady soils are usually found rich in algal content.

12.7 Microbes for Improvement of Soil Health

Soil is the definitive hub of nutrients and also a pool of various bioresources for diverse crops. There is a huge diversity of microbes that are harboured by the soil which assist as potent mediators for recycling, sequestration, and supply of different nutrients to plants. The soil microflora also performs a diverse array of tasks like mineral chelation, suppression of pathogens, enhancement of soil aggregation, aids plants in toleration of different kinds of stresses and bioremediation of the soils by producing various metabolites (Sahu et al. 2019; Sharma et al. 2019) which constitutively improves soil health (Fig. 12.2). The creation of microenvironments in the rhizosphere of plants is a hub for microbial diversity as well as different kinds of interactions that aids plant as well as soil health. Regular microbial populations of

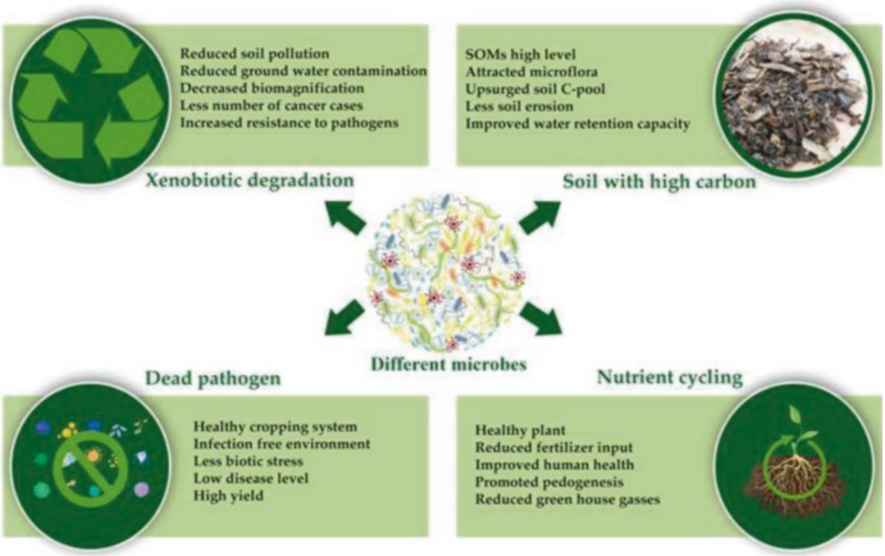

Fig. 12.2 Beneficial attributes of soil microbes for improving soil health

soils are crucial in the degradation of pollutants (Fierer 2017). If a soil face contamination, the native microbiome of the soil amends and acclimatizes to the environmental trepidation and therefore may metabolize the exterior pollutant (Tezel and Pavlostathis 2015).

The relation between soil health and microorganisms is an unhidden and undeniable fact. Therefore, the relation between microorganisms and soil health is very important. The amalgamation of the organic amendment along with abridged tillage residue administration is an emerging trend for the management of nutrients which is regarded as a sustainability-intensive agricultural practice. This practice of reduced tillage also improves the physical status of soil health as this agricultural practice precludes the fate of soil erosion by water and wind (Panagos et al. 2015). This practice increases the quantity of labile carbon; therefore, it acts as a bait for microbial dynamics as microbes are the prime utilizers of this labile carbon (Murphy et al. 2007).

There is a succession of enzymes for the decomposition of this organic matter which thereby increases the soil organic matter pool as well as microbial biomass of the soil systems (Nevins et al. 2018). Thus, this increase in microbial activity of the soil significantly improves soil health as well as soil quality.

12.8 Practices for Improving Soil Biology

The amendments of the soil with biochar are another important trait for improving soil biological status thus enhancing soil health. Biochar is the solid carbonaceous produce that originates from the pyrolysis involving waste biomass in an oxygen deficient environment. It finds great applications in the agroecosystems for the enhancement of soil carbon sequestration as well as soil fertility (Bamminger et al. 2017). The application of biochar modifies the copiousness of soil microflora in several ways. It modifies the environment which is inhabited by the microbes by supplying nutrients and altering the soil pH. It is a direct source of energy and carbon-rich substrate for the microbes and it also provides habitats for the proliferation of microbes (Dai et al. 2018).

Soil erosion is considered an important factor in determining soil health. Healthy soils suffer from minimum levels of erosion. The deterioration of soil health can be checked by the cyanobacterial content of the soil. Cyanobacteria help in maintaining soil integrity by binding the soil particles together. The filaments of cyanobacteria absorb water when they come in contact with the water and may swell up to ten times their original size. Thus, the moisture is stored in the upper soil layer where many plant root systems and various other organisms live. They also play an additional straight role in assisting plant endurance and growth.

Microbes have the inherent ability of nutrient cycling and assimilation. The microbial assimilated nutrients are supplemented to the soil's systems as cherished organic matter entrenching different mineral nutrients which are released slowly for the improvement of soil quality (van der Wal and de Boer 2017). Therefore, the practice of addition of different microbial inoculants significantly contributes to soil health. The addition of fungal hyphae and arbuscular mycorrhizae are vital for the development and constancy of soil macro-aggregates. Therefore, the infection of mycorrhiza in the soil is also considered as an indicator of decent soil aggregation. Therefore, it can be truly said that the precise use, as well as management of microbes, can significantly improve the physical, chemical as well as biological health of the soil.

12.9 Relation Between Soil Health, Microbes, and Sustainable Agriculture

It is a general estimate that a usual gram of soil comprehends a bacterial population of around 90–100 million and fungal population of nearly 2 lakhs. The majority of these organisms usually inhabit the roots of the plants. The high microbial population of microbes in the roots is the result of the secretion of root exudates by the roots of the plants. A large proportion of the carbon fixed by the process of photosynthesis is lost by the process of root exudation as bait for attracting microorganisms. The exudates are often utilized by the microorganisms as a source of food and the microbial interactions with the plants can be constructive, destructive, or unbiased for the plant. The microflora hired by the roots of plants favors the constructive interactions between the different rhizospheric components that indirectly improve soil health as well as plant growth.

12.9.1 Carbon Sequestration

Soil is deliberated to be the major carbon pool, attributable to its capability of holding carbon in an amount greater than the atmosphere and vegetation collectively. The organic matter sustaining the soil systems is mainly composed of organic portions represented by decayed animals and plants along with the microorganisms, besides inorganic forms for instance carbonates and lime. The organic portion of soil carbon is largely derived from atmospheric carbon dioxide which is fixed by plants and autotrophic microbiota by the process of photosynthesis where the inorganic form of carbon is transformed into organic carbon, for instance, sugar and cellulose, for the maintenance of cellular integrity in the form of cellular biomass. The amount of carbon sustaining in the soil systems is around 2344–2500 Gigatonne. A major portion of this, about 1550 Gigatonne of carbon is stored in organic forms and 950 Gigatonne is stored in inorganic forms.

The process which increases the soil organic carbon by removing carbon dioxide from the atmosphere coupled with its introduction into the soil is said to be carbon sequestration. The more carbon stored in the soil and less carbon lost specifies that the land is highly capable of carbon sequestration, and vice versa. The process of photosynthesis either by plants or microorganisms contributes to carbon sequestration process whereas respiration and decomposition add to carbon loss from the terrestrial ecosystems. Plants allot about 40% of photosynthetically fixed carbon to the soil by a process named as rhizodeposition. Plants secrete several organic compounds through their roots which are popularly known as root exudates and serve as nutrients for the soil biota thereby attract an enhanced level of microbial activity in the rhizospheric portion.

However, plants are not the sole contributors to soil organic carbon. The quest for the processes for enhancing carbon sequestration in the soil systems coupled with a reduction in the carbon losses and emissions has put forward the involvement of certain microbial inoculants for their paramount roles in this process. The involvement of appropriate microorganisms endowed with the veracious mechanism for specific soils is of great importance to upsurge carbon sequestration in soils as alterations in the succession of microbial communities strongly affect the soil organic matter cycling as well as storage due to the ability of soil microorganisms to regulate inputs of multiple pathways and loss of soil carbon (Ahmed et al. 2018).

When microbial carbon sequestration is taken into consideration it unveils a diverse array of mechanisms involved in upsurging soil carbon pool, such as, the aptitude to deposit carbonates, the formation of headstrong vegetative tissues and products, and the ability to form stable forms such as soil aggregates that protect carbon soil organic forms. In dryland ecosystems, the soil organic carbon pool is largely contributed by its microbial inhabitants by secreting exopolysaccharides secreting and by forming filaments networks. Such processes not only add to the soil organic carbon pool but also protect the soil from erosion and other factors targeting soil degradation.

Such possessions of soil microbes enhance the water retention capacity of the soil and also increase the nutrient soil fertility by accumulating other nutrients into the soil in the form of their biomass as well as metabolites. These processes of microbial systems can also lead to the creation of suitable soil conditions for the proliferation of other organisms such as mosses, lichens, and herbaceous and perennial plants thereby increasing the C storage potential (Kheirfam 2019). Therefore, it can also be said that microbes also play suitable roles for indirect sequestration of soil carbon by creating conditions and environments suitable for the growth of plants which in turn sequester more carbon from atmospheric carbon dioxide.

The functioning of microbial communities is directly affected by the elevated levels of atmospheric carbon dioxide, for instance, it has been noted that the plant interactions with arbuscular mycorrhizal fungi are greatly enhanced under higher carbon dioxide levels. The higher carbon dioxide levels increase the external as well as internal hyphae due to the enhanced root biomass and higher distribution of fixed carbon to the external hyphae. The microbial contribution of fixed carbon to the soil is largely governed by the microbial growth efficiency *i.e.*, the amount of new biomass carbon produced per unit substrate carbon metabolized, degree of protection of microbial biomass in the soil, and the rate at which microbial by-products are decomposed by other microorganisms. Thus, the fate of microbially sequestered carbon is largely governed by their rates of degradation and their extent of recalcitrance.

The bacterial communities prevailing in soil ecosystems are largely associated with decomposition and carbon dioxide respiration, therefore, they present a low carbon assimilation efficiency as compared to fungi-dominated microbial communities. The fungal cell walls are comprised of polymers of melanin and chitin and are resilient towards degradation while phospholipids are the main constituents of the bacterial cell wall which are energy-rich and are readily decomposable substrates and are easily accessible to a vast array of soil microbes. Therefore, the soil carbon pool is anticipated to be more tenacious when mediated by fungal biomass and more labile when facilitated by bacterial biomass (Grover et al. 2015).

12.9.2 Nutrient Cycling

Soil systems are greatly acknowledged for supporting a greater range of life and here the conception is analogous to human health; it is not difficult to understand or recognize when the system is viewed as a whole. The microbiological aspect of soil ecosystems, ranging from genes and species to communities, is largely responsible for the strength of healthy soils. This competent rhizospheric microbiota represents a vital constituent of soil habitat which is acknowledged for playing important roles in the functioning and possessions of soil-plant systems by controlling the nutrient cycling reactions crucial for supporting soil quality as well as for subsidizing the process of pedogenesis along with its maintenance. The process of nutrient cycling maintains the healthy status of soil and plant systems along with the regulation of the flow, root growth, and storage of nutrients. Surprisingly, the fertilizers added for the plant growth promotion and yield enhancement have to pass through the competent rhizospheric microorganisms before being utilized by the plant systems.

The soil organic matter which acts as a prime source of phosphorus, sulfur, and nitrogen is decomposed by the native soil microbes to its own components or subcomponents with the help of several enzymes like amylase, arylsulfatase, cellulase, chitinase, dehydrogenase, phosphatase, and urease. This process of mineralization of organic matter is a biological process of paramount significance where the organic compounds present in organic matter are biochemically transformed by the soil microbes to simpler organic compounds and mineralized nutrients. The residues of dead plants and animals represent a greater pool of nutrients that is added to biogeochemical cycling by the microbial activities targeting its decomposition to simpler forms. The residues are often classified as easily degradable, moderately degradable, and difficultly degradable which are utilized as substrates by different classes of microorganisms. The oxidation of numerous elements of biological importance at different rates like nitrogen, carbon, sulfur, phosphorus, etc. during mineralization of organic matter is of supreme prominence to the plants. Microbes are largely responsible for the conversion of such elements into usable forms for use by the plants (Sahu et al. 2017).

12.9.3 Degradation of Xenobiotic Substances

A large number of unusual organic compounds have been discovered and synthesized by human beings in the last century and many of these compounds are xenobiotic in nature. These synthetic chemicals have largely found applications as refrigerants, solvents, dyes, pesticides, and other compounds of importance in agricultural systems (Duong et al. 1997). Undoubtedly, pesticides play an important role in modern agriculture and have greatly contributed to combatting global hunger problem but these chemicals are not degraded easily by the biological processes (Villarreal-Chiu et al. 2017). The xenobiotic compounds also pose various other health hazards. According to *United States Environmental Protection Agenc*y, 90% of fungicides, 60% of herbicides, and 30% of insecticides are recognized as potentially cancer-causing (Grube et al. 2011). The pesticide production in India started in 1952 with the production of benzene hexachloride which was further followed by dichlorodiphenyltrichloroethane.

Subsequently, the patterns of production along with their consumption have amplified enormously and are attributable to their assorted applications. At present, India is the second leading producer of pesticides in Asia with a twelfth global rank (Gupta 2004). The extensive usage of xenobiotic compounds has significantly deteriorated the soil health along with several other harmful effects including dwindled soil fertility, nitrate leaching, soil acidification, increased resistance in flora and fauna, pollution of groundwater along with the surface water, and impurity of the agricultural soils (Kumar et al. 2018). Consequently, the degradation of such compounds by either physicochemical or biological processes has been greatly researched. Therefore, the microbial ability to degrade such contaminants seems to be a preferred method that can contribute to restoring soil health.

The native microbial diversity of the contaminated regions is usually explored by scientists in the quest for indigenous bacteria having the capability of utilization and degradation of an extensive variety of pollutants (Stroud et al. 2007). Several bacterial genera have the capability of biotransformation of such organic contaminants in their natural environments. The members of the microbial genera like *Cladosporium*, *Flavobacterium*, *Aspergillus*, *Arthrobacter*, *Flavobacterium*, *Pseudomonas*, *Bacillus*, *Stenotrophomonas*, and *Burkholderia* etc. can be utilized for degrading the contaminants for restoring soil health (Kumar et al. 2018). The approach of rhizosphere engineering and microbial consortia having specialized functions like degradation of polycyclic aromatic hydrocarbons is evolving new tools and methodologies for amelioration of such problematic soil (De Roy et al. 2014).

12.9.4 Soil Suppressiveness

The capacity of soil to regulate the flow of soil-borne pathogens is called soil suppressiveness. The level of disease is found to be minimum in healthy soils thus they provide infection-free environments for the germination of seeds during an initial phase of development of the plants. Several soil systems are found to be inherently capable of suppressing the soil-borne pathogens to a definite magnitude, which proves to be a highly robust and anticipated tool for the development of healthy cropping systems with a decreased reliance on chemical inputs. This capability of the soil to suppress pathogens is a result of different physical, chemical as well as biological parameters of the soil. The biological properties of soil, especially microbiological, are known to play crucial roles in soil suppressiveness.

The general suppressiveness of soil systems is largely governed by the biomass, activity as well as the diversity of the microorganisms inhabiting the soil. The non-pathogenic microbial inhabitants of soil reward the suppressiveness to soil as a result of their capability to compete with the pathogenic microbes. Furthermore, there are different mechanisms by which the growth of a pathogenic organism is suppressed like the production of hydrogen cyanide, surfactins, salicylate and catechol-type siderophores, lipopeptide, iturin etc. (Arthee and Marimuthu 2016).

The other form of soil suppressive is called specific soil suppressiveness which targets the inhibition of specific pathogens. It occurs due to the presence of specific microbial taxa or groups in the soil which inhibits the growth of specific pathogens by their antagonistic behaviors. This type of suppressiveness is considered to be less persistent in the soil as compared to generalized suppressiveness. However, soil suppressiveness undoubtedly instigates from the combined effects of general and specific soil suppressiveness (Bongiorno et al. 2019).

12.10 Conclusion

The realm of agriculture has to confront an expansive gamut of challenges of climatic changes, stagnant crop yield, nutrient deficiency, deterioration of soil organic matter, availability of water, and dwindling cultivable land. Although green revolution proved to be an act of paramount success; the excessive usage of chemical fertilizers, pesticides, and other land-use practices has resulted in stagnant crop production. Furthermore, soil proves to be the ultimate sink for each type of chemical. As these chemicals are non-biodegradable, they prevail in the soil for a very long time and deteriorate the soil health. Besides soil health deterioration, they also enter the food chain and cause various health-related hazards. Therefore, the demand of the hour is cleaner and chemical-free food production along with the management of soil health. Soil health is also adversely affected by various human-mediated management practices.

The soil can be rejuvenated by the application of microorganisms as they possess various properties which improve the physical as well as chemical properties of the soil. In addition to it, microorganisms also possess the unique trait of carbon sequestration which adds to the organic carbon pool of the soil. The microbes also have the great potential to transform the normal soils into soil systems which are found to be suppressive for various pathogens. Such attributes of microbes decrease the reliance on chemical inputs thereby advocate sustainability.

Healthy soil is found to inhabit a vast variety of microbes in varying numbers and the status of such soil microbiota can be enhanced by various agricultural practices like no-tillage, amendments of organic matter, mulching, and crop rotation. The declining status of soil health needs a strong microbiological intervention for revitalizing it as all forms of life depend on the soil ecosystems directly or indirectly. Thus, it can be concluded that the tremendous potential of soil microbes than any other life form can be utilized effectively for uplifting the status of soil systems but more research is required in the field to combat the various problems. The ever-increasing problems can be solved by the judicious use of microorganisms by keeping in mind the fact that “the role of infinitely small is infinitely large in nature”.

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