Applications of Microbes in Soil Health Maintenance for Agricultural Applications

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Abstract

Agriculture is integral to the world economy and as a means to feed the world populace. The priorities can be multipronged including to overcome famine and eradicate poverty; for economic diversification, industrialization, and investments; and to ensure sustainable resource utilization and environmental management. The excessive utilization of chemical fertilizers, though managed to improve the yield, also kills the pests, weeds, and microflora, with destructive impact on the natural ecosystem. Plant-associated microbes have great potentials to assist in enhancing the yield and plant resilience against pests and diseases. Genetic technology using microorganisms and their metabolites has been applied to increase the nutrient uptake and productivity and control plant stresses and responses to pests. Microbiological tools could enhance environmental health and promote agricultural sustainability. However, the side effects of microbial residents and contaminants must be addressed. This chapter discusses the functions and contributions of microorganisms in promoting health and fertility

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of soil. Different types of microbial sources and strains are highlighted. The use of natural and biological-based fertilizers, pesticides, herbicides, and insecticides in agriculture is elaborated. The importance of microbiome for sustainable agriculture and soil and environmental health is discussed.

Keywords

Agricultural soil · Microbes · Soil health · Biofertilizers · Biopesticides · Bioherbicides · Bioinsecticides · Bioremediation · Microbiome · Sustainable agriculture

Abbreviations

BI	BioDesign Institute
CEB	Center for Environmental Biotechnology
ISR	Induction of Systemic Resistance

12.1 Introduction

Human population is expected to reach nine billion by the year 2050, which may lead to the need to increase the food yield by 70%, from the current productivity. To meet the increasing demand of food supply, the quality of the crop and output must be enhanced, and this is very much dependent on the soil health for agricultural applications. The interactions between plants and the ecosystems where the biodiversity and microbial communities can thrive in symbiosis must be understood. Conservation of soil health ensures steady supply of food (Atapattu and Kodituwakku 2009). Soil health refers to the soil ecosystem and the ability of the soil to adapt to agronomic activities and various environmental conditions and also enhance the crop yield and improve plant health (Kibblewhite et al. 2008; Lal 2016). The fertility of the soil is dependent on the physical, chemical, and biological factors. The physical characteristics of the soil include the texture, structure, and architecture and water retention capability. The chemical conditions of the soil include the salinity, acidity, and alkalinity, while the biological factor constitutes the microbial communities residing in the soil (Johns 2017). Microbes are the most diversified groups of the organisms making up more than half of the biomass on earth (Bar-On et al. 2018).These microbes have significant functions in sustaining the biogeochemical cycles, and the plants have significant contributions to maintain the food chain by utilizing the microbes present in the soil (Curtis and Sloan 2005).

The microbial population includes microalgae, cyanobacteria, fungi, actinomycetes, bacteria, and lichens. These microbiota are present in the biological soil crust (BSC), the uppermost part of the earth, and could play a major role in enhancing agricultural productivity (Manjunath et al. 2016). Photosynthetic carbon is deposited in the plant roots. The root system and the rhizospheric zone are therefore important areas of microbial activities and their interactions with the plants. Microbiota acting as bioinoculants promote plant growth by establishing symbiosis in the root system. Among the beneficial microbiota for plants are plant growth-promoting rhizobacteria (PGPR) and plant growth-promoting fungi (PGPF) (Singh et al. 2017). Diversified metabolic activities of various microbes contribute towards the provision of major elements such as phosphorus, potassium, and carbon, influencing the soil characteristics and ultimately the crop yield. The diversity and abundance of the microbial resources are therefore important to be conserved. The soil microbes, especially the bacteria and fungi, involve in the recycling of the nutrients and the detoxification and recycling of wastes for soil health and agricultural practices (Singh et al. 2017; Aislabie et al. 2013; De Vero et al. 2019).

12.2 Microbial Sources

12.2.1 Microalgae and Cyanobacteria

Microalgae and cyanobacteria are "beneficial microbes" and important components of the food web, having the ability to grow in extreme environments. Microalgal species such as *Chlorococcum*, *Chlamydomonas*, and *Scenedesmus* produce polysaccharides, while cyanobacteria are known specifically for having nitrogen-fixing capacities (Singh et al. 2011). The importance of cyanobacteria, as illustrated in Fig. 12.1, includes in the recycling of nutrients, decomposition of organic wastes, degradation of toxic chemicals, and as producers of metabolites such as enzymes, hormones, etc. which are essential for soil health and plant growth (Mallavarapu et al. 2000; Renuka et al. 2018).

Excessive farming practices make agricultural lands more vulnerable and are the leading cause of decrease in soil fertility, with 30% of the farmable land undergoes soil degradation. Among all soil microbes, 27% of the total biomass contribution is from microalgae (Abinandan et al. 2019). During climatic changes, green algae and cyanobacteria are responsible for the production of organic content. High organic matter in the soil can be the result of algal cell lysis which releases exopolysaccharides, leading to increased oxidizable carbon in the soil which is the necessary constituent of organic matter. This organic matter is the source of carbon available to plants and also for the growth of soil microorganisms. In order to prevent the leaching of minerals, algae are in competition with higher plants. A few species of *Cyanobacteria* like *Nostoc* colonize root systems of plants which ease the transportation of minerals and metabolites as well (Osman et al. 2010; Li et al. 2010; Svircev et al. 1997).

Cyanobacterial biofilms when used under non-flooded conditions aid in nitrogen fixation and solubilization of phosphate, necessary for plant growth (Prasanna et al. 2014). Cyanobacteria is responsible for the production of oxidizable and soluble carbon along with enhanced paddy yield, in post-harvested soil. Besides carbon residues, cyanobacterial inoculation promotes grain yield, which is responsible for

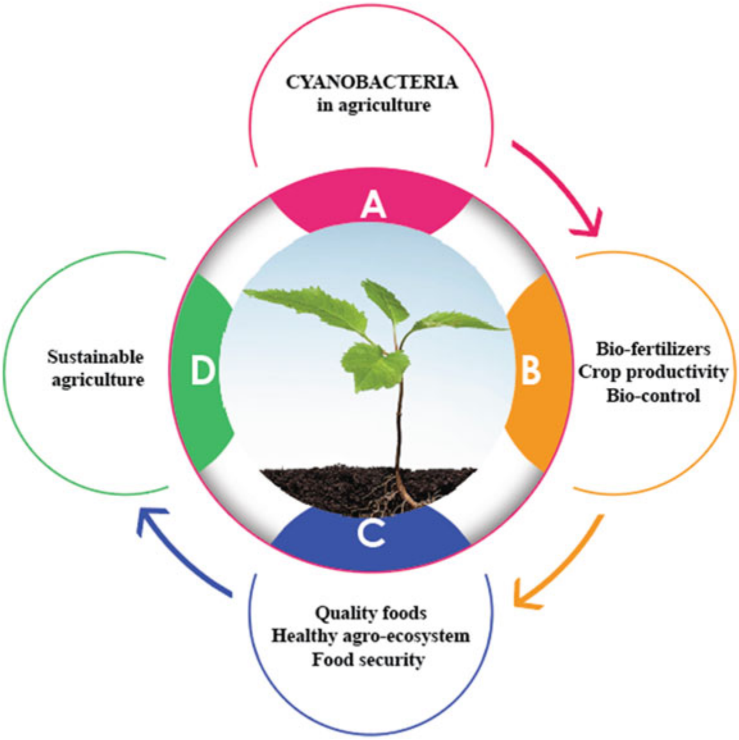

Fig. 12.1 Importance of cyanobacteria in agriculture

plant growth, without utilizing manure. Next to nitrogen is the organic phosphorus present in the upper layer of the soil, which is 20–80% of the total phosphorus (de Mulé et al. 1999; Steffens et al. 2010). Phosphate-solubilizing bacteria convert insoluble phosphate to soluble form, which is readily taken up by the plants. However, soil microalgae incorporate inorganic phosphates and convert it into polyphosphates by making it readily available to plants. Furthermore, cyanobacteria can also produce enzymes that are responsible for the degeneration of inorganic phosphate, making it available to plants. They can also solubilize mineral rock having phosphates in it by producing phthalic acid (Sharma et al. 2013; Whitton et al. 1991).

Cyanobacterial biofilm fertilizers have caught attention owing to the lesser quantity of chemical fertilizers used and also because of lower cost. Cyanobacterial films made of *Anabaena-Trichoderma viride* enhance maize hybrid production by conserving 60 kg per ha and raise accessible N_2 in soil from 20 to 60 kg/hectare (Prasanna et al. 2015). Likewise, biofilms utilizing different species like *Anabaena-Serratia* and *Anabaena-Pseudomonas* result in phosphate activities and acetylene reduction in wheat cultivation. Biofilms increase the content of soil micronutrients like iron (13–46%) and zinc (15–41%) (Adak et al. 2016).

30% of the total land undergoes degradation, and the degraded soils contain saline, alkaline, and acid sulfate which can be improved with the use of fertilizers. These, however, can have harmful effects on soil health. Soil characteristics can be restored with the application of microbes. Combinations of cyanobacterial modifications and natural chemical additives can have big impacts on the soil stability along with improving its water holding capacity (Nkonya et al. 2016; Xiong et al. 2018). Soil health is about maintaining the balance between soil organisms and their surroundings. Soil algae synthesize some compounds which are hydrophobic in nature and may exhibit water repellence characteristics. Algal metabolites which are hydrophobic in nature, help to halt soildegradation by binding the mineral particles (Doerr et al. 2000; Malam Issa et al. 2009).

12.2.2 Fungi

Fungi are among the most significant class of microbes which are beneficial for the growth and productivity of plants and crops (Karun et al. 2018). Useful fungi assist plant development by enhancing solubility of micronutrients (Zn, P,K) and release of plant growth regulators (gibberellins, auxin, ethylene, and cytokinin) and the release of enzymes (gluconase, cellulases, and glycosidase which aid in cell wall lysis) (Ahmed Nouh 2019; Pandya and Saraf 2010). They degrade the soil organic matter and maintain the nutrient and carbon balance. Certain species of fungi are sorbents of harmful metals like Cd, Cu, Hg, Pb, and Zn and entrap these toxic metals into their fruit-bearing bodies (Žifčáková et al. 2016; Baldrian 2003).

Soil fungi, depending on their functions, are categorized into three types: as biological controllers, as regulators of ecosystem, and for the degradation of organic waste matter and bioconversion of compounds (Gardi et al. 2009). Species which act as regulators of ecosystem regulate physiological processes in soil and determine the soil structure formation. Biological controllers maintain the progression of various organisms present in the plants' soil as mycorrhizal fungi regulate uptake of nutrients and enhance plant growth (Bagyaraj and Revanna 2017). Fungal communities influence the growth of plant through mechanisms like mutualism and cyclization effect, and availability of nutrients. Fungi also stabilize organic matter of the soil, necessary for soil health, and play important part in nitrogen fixation, production of hormone, and root pathogen control (Wagg et al. 2014; Hannula and van Veen 2016; Treseder and Lennon 2015; Jayne and Quigley 2014; Baum et al. 2015).

The health of soil is determined by its capability to sustain ecosystem, maintain biological productivity, and improve the well-being of plants and other living organisms (humans and animals). Biodiversity of soil fungal has major role in upgrading the quality of soil and agricultural productivity. Fungi transfer nutrients necessary for plant development through the decomposition of organic matter. They shield the plants against pathogenic microbes which otherwise would affect the soil health. Soil management is therefore essential to ensure future production of food and to minimize soil degradation. Fungal communities are responsible in establishing the plant biodiversity, ecosystem, and productivity (Wagg et al. 2014;

Frac et al. 2015; Abawi and Widmer 2000). Arbuscular mycorrhizal fungi (AMF) are among the useful microbes in soils significant for agricultural purposes. Inoculation with AMF has major contribution towards increasing the crop yield. AMF symbiosis improves root and plant growth, promotes soil architecture, encourages nutrient cyclization, and improves plant resistance to stressful conditions, and enhances uptake of diffusion-limited nutrients like P, Zn and Cu (Smith and Read 2010; Thilagar and Bagyaraj 2013).

Some antagonistic fungi like *Glomus* or *Trichoderma* species are used to fight plant diseases caused by fungal pathogens. *Trichoderma* sp. (*Pythium*, *Phoma*, *Fusarium*, *Alternaria*, *Sclerotinia*, *Botrytis*, etc.) could inhibit over 60% of pathogenic species on plants such as cucumbers, peppers, cabbages, tomatoes, cereals, and ornamentals. Various species of *Trichoderma* such as *T. virens*, *T. atroviride*, *T. asperellum*, *T. harzianum*, and *T. viride* play important role in biological control and are termed as biostimulants for agricultural crops. Other contributions of fungi necessary for plant and soil health are inoculation by microbial association of AMF with PGPR and other microbes important in nitrogen fixation and phosphorus solubilization. AMF and PGPR influence the development of plant and microbial diversity, and soil activity (Dawidziuk et al. 2016; López-Bucio et al. 2015).

Genera *Fusarium*, *Rhizoctonia*, *Phytophthora*, and *Pythium* are the main associations of pathogenic fungi which are present in soil and are of much significance globally as well as on local level. Biodiversity of soil fungi and techniques to enhance the communities of beneficial fungal species are important for soil protection and sustained plant yield (Frąc et al. 2018). For example, *Beauveria bassiana* are naturally-occuring fungi and *Metarhizium anisopliae* are entomopathogenic fungi. The spores originating from these fungi germinate and nourish upon coming into contact with the target insect cuticle and kill the insect by draining its nutrients. The mycelium of *Verticillium lecanii*, an entomopathogenic fungi, releases toxin cyclodepsipeptide, termed as bassianolide, and other toxins (like dipicolinic acid), which poison scale insects, whiteflies, and aphids, leading to their death. *L. lecanii* species are employed in agriculture and horticulture as biological pesticide and control insect pests like whiteflies, aphids, etc. (Singh et al. 2017).

12.2.3 Bacteria

Bacteria, being the most abundant organisms on earth, could easily make up more than 10^{11} (100 billion) cell numbers in one teaspoon of agricultural soil. As an important group of soil microbes, bacteria perform variety of different functions in recycling of nutrients, water dynamics, and disease alleviation. Some bacteria release substances which aid in binding of soil particles and transform them into small aggregates and thereby influence water mobility. These aggregates promote water penetration and water holding capacity of soil. In addition, various bacterial species fight against pathogens in plant roots (Knudsen 2006).

Depending on functions, bacteria fall into four categories. Majority of bacteria are decomposers which convert soil organic matter into other forms beneficial to the organisms in soil. Besides this, they decompose pesticides and contaminants in soil, thereby increasing soil health. Mutualists constitute the second group of bacteria that establish associations with plants. Nitrogen-fixing bacteria are the best among mutualists. Pathogenic bacteria comprise the third group which include the following species: *Zymomonas*, *Erwinia*, and few species from *Agrobacterium*. Lithotrophs, also called chemoautotrophs, are the fourth group which make use of the N, S, Fe, and H, rather than the carbon compounds, and play important part in nitrogen cycling and detoxification of contaminants (Ingham et al. 1985). *Rhizobium* genus involves nitrogen-fixing bacteria through symbiotic associations and includes *Rhizobium leguminosarum*, *Rhizobium tripoli*, *Rhizobium phaseoli*, *Rhizobium lupine*, *Rhizobium meliloti*, and *Rhizobium japonicum* (Young et al. 2006).

PGPR (the term introduced by Joe Kloepper in the 1980s) include *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Pseudomonas putida*. PGPR are responsible for inducing resistance in plants against viral, bacterial, and fungal diseases and other insects, and this mechanism is called Induced Systemic Resistance (ISR). In agriculture and horticulture, *Bacillus polymyxa* is employed as inoculants where the plants are shielded by these biofilms from pathogens. Synergism between bacteria and plant roots changes the physical characteristics of the root hairs (Lavakush et al. 2014; Yegorenkova et al. 2013).

Pseudomonas fluorescens, a non-pathogenic PGPR, enhance plant development, control damage caused by pathogens, and stabilize plant roots. They have tremendous influence on plant development utilizing direct or indirect mechanisms. *Kocuria turfanensis* isolated from rhizospheric soil is capable of solubilizing phosphate and producing indole-3-acetic acid (IAA, a plant hormone important in microbe-plant interactions) (Prasad et al. 2015). *Frateuria aurantia*, a Potassium-mobilizing *Proteobacteria*, has the ability to mobilize usable potash to the plant roots or soil. It can perform its function in any type of soil, more specifically in soil low in potassium content, thereby enhancing the soil health (Johansen et al. 2005).

12.3 Applications of Microbes

12.3.1 Plant Growth Regulators

Plant growth regulators, either synthetic or naturally produced hormones, are important in agriculture to control plant growth and development. These may not be hazardous if utilized as per the recommendation at the right dosage. Microbes residing in the rhizosphere of the plants also have the ability to produce and supply auxin, a regulator of plant growth, as secondary metabolites. The plant morphological changes can be the consequence of the various ratios of plant hormones produced by the rhizosphere bacteria and roots. The production of compounds which possess physiological impacts on the development and growth of plants involves different soil microbes like fungi, bacteria, and algae (Ahemad and Kibret 2014). These include by transforming the plant growth root structure to promote rhizobacteria

(PGPR) and promoting phytohormones like IAA, cytokinins, and gibberellic acid and the synthesis of metabolites such as antimicrobials. There are many PGPR and symbiotic, pathogenic, and free rhizobacterial species which produce auxins in the rhizosphere to induce and increase root formation (Han et al. 2005). Many beneficial fungi are associated with the antagonistic effects on the pathogenic fungi, by synthesizing antibiotics, and involved in the plant defense mechanisms by infecting the spores, hyphae, or sclerotia of pathogenic fungi, thereby taking part in biological control (Mejía et al. 2008). A number of degradable enzymes are produced, e.g., cytinases, gluconates, and proteins, as biological control agents. Many *Trichoderma* strains have colonized various plant roots, thereby importantly improving the development and growth of plant. In *Arabidopsis*, *Trichoderma virens* promotes both biomass and lateral root growth via an auxin-dependent mechanism (Contreras-Cornejo et al. 2009). The synthesis of *Sm1* (small protein 1), an elicitor protein, is normally linked to the promotion of the systemic and local resistance (Živković et al. 2010).

Phosphorus is obtained by the plants from the earth in the form of phosphate. The mobility of this element is very less in the plant unlike other macronutrients. The role of phosphorus-soluble microorganisms (PSMs) is therefore significant in phosphorus-based nutrition, increasing their supply to plants by releasing organic and mineral soil P pools through solvent and mineralization (Kalayu 2019). The mechanisms which are involved in the solubility of phosphorus include by reducing the soil pH through microbial organic acids and mineralization of organic phosphorus by acid phosphatase. Maximum adaptability of phosphorus-soluble bacteria (PSB) is feasible in association with other mycorrhizal fungi or beneficial bacteria (Satyaprakash et al. 2017). Bacteria are found to be more capable than fungi for phosphorus solubility (Sharma et al. 2013). Advantageous microflora, e.g., *Penicillium*, produces an organic acid that diffuses the phosphate in the soil to be easily utilized by the plant roots. In soil bacterial communities, heterozygous species of *Bacillus* and *Pseudomonas*, *Enterobacter*, and endosymbiotic *Rhizobia* have been reported as productive types of phosphate solvents. The latest estimate is that PSB is around 1–50% in common soils, whereas phosphate-soluble fungi make up about 0.1–0.5% of the population (Panhwar et al. 2011).

Potassium (K) is a significant component of plant nutrition which performs numerous biological activities to sustain the quality of plant growth. Potassium is normally found in soil in large amount. The total potassium content on the top surface of the soil is in the range of 3000–1,000,000 kg/ha (Bertsch and Thomas 1985). There are four distinct forms of potassium in water: soluble, interchangeable, non-interchangeable, and structural or mineral soils (Sparks and Huang 1985). The quantity of potassium delivered by the soil depends on the variation in the parameters of soil, e.g., pH, texture, moisture content, soil tiling, oxygen level, and temperature, and topographical and biochemistry (Basak and Biswas 2008). Feldspars are a group of rocks made up of mica, potash, or rock phosphate, where potassium can be extracted through microbial reactions and plants, converting the unavailable K organic acids into available form and secreted during the nutrient cycle (Sessitsch et al. 2013).

12.3.2 Volatile Organic Compounds (VOCs)

Compounds possessing low molecular weight (<300 g/mol) such as alcohol, ketones, aldehydes, and hydrocarbons are among the common VOCs (Choudhary et al. 2008). These may be a signaling response between plants and the microbes, and the VOCs typically exhibit coordinated responses to the numerous stimuli in plants and microorganisms (Ortíz-Castro et al. 2009). VOCs are highly vaporizing under normal conditions, and they enter the atmosphere resulting in an increase in vapor pressures. *Arabidopsis* rhizosphere has been detected with VOC emission, attributable to the biological stressors (Steeghs et al. 2004). Many volatile substances, e.g., alcohol, acids, ketones, aldehydes, terpenes, and esters, are constitutionally produced or specifically induced due to different negative or positive interactions with microorganisms. The excretion of VOCs, e.g., 2,3-butanediol and acetoin, from PGPR strains such as *Bacillus amyloliquefaciens*, *B. subtilis*, and *Enterobacter cloacea*, enhance the development of *Arabidopsis thaliana* significantly with the production of bioactive VOCs (Ryu et al. 2004). Rhizobacterial strains emit VOCs which can behave as signaling molecules to the plant to react with microorganism, and this ultimately triggers the response of plant towards the colonizing microflora. Plant volatiles with lower molecular mass, e.g., green leaf components and terpenes, behave as signaling molecules for various organisms living at different trophic levels (Farmer 2001). It is important to understand the mechanism of VOCs against the pathogens in plants, and the building up of volatile components in the plant-rhizobacteria system and in nature.

12.3.3 Biotic Elicitors

Elicitors are involved in the mechanisms of plant defense (Thakur and Sohal 2013). Elicitor molecules such as methyl jasmonate, salicylic acid, and Nitric oxide (NO), induce the production of secondary metabolites, e.g., phytoalexins, glucosinolates, and alkamides, as stress responses, for example, to microbial pathogens (Yang et al. 1997). Jasmonic acid and methyl esters of jasmonic acid are signalling transducers in the cell suspension cultures of *Rauvolfia canescens* and *Eschscholzia californica* upon treatment with yeast elicitor (Roberts and Shuler 1997). Jasmonic acid elicitor reduces cell growth of *Morinda elliptica* but with enhanced anthraquinones, total carotenoids, vitamin C and E, and lipid peroxidation and hydrogen peroxide levels. With 6 days treatment, glutathione reductase enzymes are elevated, while ascorbate peroxidase level is only half that of control, and catalase is completely reduced (Chong et al. 2005). The molecular basis of signalling exchange between microbial pathogens and the hosts necessitates characterization and purification of specific elicitor-binding proteins which ultimately lead to the activation of defence mechanism.

12.3.4 Bioremediation

Bacteria, archaea, and fungi play an important role in bioremediation to metabolize pollutants. Microorganisms break down and eat complex molecules, convert them into innoxius, natural substances (Kumar et al. 2011), thus ultimately dispose of the pollutants rapidly and reduce the environmental pollution. The organisms employed in the bioremediation process are known as bioremediators and a process in which a fungi is utilized to remediate certain area is called mycoremediation (Rhodes 2014). The fungal mycelium secretes acids and extracellular enzymes that are capable of breaking down the plant fibers including cellulose and lignin. Wood thin fungi are specifically efficient in the decomposition of harmful constituents of petroleum and aromatic pollutants such as chlorinated compounds (Rhodes 2014). Mycofiltration removes water wastes and microorganisms using fungal mycelia to filter the soil. Various REDOX reactions are generally performed by the bioremediators for the oxidation of toxic contaminants. However, this may require the right microbial species to oxidize specific pollutant to achieve effective bioremediation.

During drought, plants regulate physiological responses such as the increase in abscisic acid content, accumulation of specific metabolites, expression of aquaporin, and vacuolar H-pyrophosphatase to maintain cell homeostasis through osmotic adjustment (Gornall et al. 2010). Concentrations of ethylene reach higher levels, which inhibit the plant growth and thereby enhance the root-to-shoot ratio. Therefore, the large-scale root system increases the area of water absorption. There are also accumulations of Reactive Oxygen Species (ROS) that may significantly affect the cell integrity, function, and plant survival. Optimal microbial colonization may involve the endosphere and the rhizosphere where mycorrhizal fungi and plant-growth promoting bacteria (PGPB) can modulate bacterial physiological responses (Vacheron et al. 2013) and thereby help to enhance the plant tolerance under severe environmental conditions. Pot and in vitro experiments have confirmed the ability of endosphere and rhizosphere bacteria to improve tolerance of plant during growth and stress. Microbial vaccines, for instance, increase growth of plant up to 40%, indicating the potential of PGP microorganisms in agriculture (Pérez-Montaño et al. 2014). The role of microorganisms in the adaptation of plants towards drought may depend on the composition of microbiome which varies greatly in a specific ecological state (Marasco et al. 2012), as it also depends on the taxonomic characteristic of the respective plant species.

Adventitious microbes can inhibit the development of phytopathogens by competing for nutrients and space, thus reducing the nutrient availability to the pathogens (Marasco et al. 2012). Disease-resistant soil microflora is typically controlled via hostile microbes that are capable of creating a wide type of antibiotics (Mohseni et al. 2013). *Penicillium*, *Aspergillus*, *Trichoderma*, and the antagonistic actinomycetes are producers of various antibiotics. Many species of *Trichoderma* are strong antagonistic invaders and the antibiotics produced by hostile microorganisms can have biological and biochemical impacts on plant pathogens present in the soil (Rahul et al. 2014).

12.3.5 Biocontrol

Microbial biopesticides and biofertilizers are the latest developments in the field of eco-friendly agriculture (Bhardwaj et al. 2014). Living microorganisms in biofertilizers are applied to the surface of plant, soil, or seeds, to colonize rhizome, and supply primary nutrients to the host (Tanti 2015). Biopesticides are the microorganisms that generate, acquire, and induce systemic resistance against the pathogens, as antibiotics, HCNs, siderophores, or hydrolytic enzymes. Native microorganisms are commonly used for the development of bioinsecticides and biopesticides as well as for pest and disease control to promote plant growth. A bacterium known as *Rhizobium* can also be used as a biofertilizer in agriculture.

Rhizobia is known for its capability to make symbiotic interactions with leguminous plants by colonizing root nodules (Bagali 2012; Wang and Martínez-Romero 2000). Nitrogen is reduced by bacteria to produce ammonia and this can provide for efficient rhizobium strains to the soil, to enhance the soil productivity and improve the growth of plant by improving nutrient availability. *Rhizobium* biofertilizer in legumes could substitute chemical N_2 by 30–35% when *Rhizobium* biofertilizer is applied together with the chemical fertilizers (Mia et al. 2010). Similarly, *Acetobacter*, *Rhizobium*, *Azorhizobium*, *Aspergillus*, *Azospirillum*, *Azotobacter*, *Penicillium*, *Bacillus*, *Pseudomonas*, etc. are also effective in promoting plant growth. However, the scientific synthesis and utilization of microbial formation is significant during the development of agriculture sustainability.

The use of competitive natural rivals to reduce the number of pathogens is known as biological control. Natural rivals include antagonists and competing microbes which destroy or prevent living pathogenic organisms. The biological control agents less harmful, simpler, and less expensive than the chemical pesticides. Bacteria are commonly introduced in the roots and seeds of plants to control different microbial attacks. For example, non-pathogenic *Streptomyces* strains control the crust of the potato caused by the scab (Neeno-Eckwall and Schottel 1999). The different functions of rhizosphere microbes are illustrated in Fig. 12.2. Antagonistic activity of *Streptomyces* is linked to the production of secondary antifungal metabolites and extracellular hydrolytic enzymes. The interaction of *Pseudomonas fluorescens* as a biocontrol against the soft rot potato pathogen *Erwinia carotovora* subsp. *atroseptica,* is attributable to the production of 2,4-diacetylphloroglucinol (Cronin et al. 1997).

The management of plant nutrient may involve the microbes enhancing the availability of the macro- and micronutrients in the rhizosphere through the microbial-community consortium. These include associative N_2 fixation, reduced levels of ethylene, and the assembly of phytohormones, siderophores and regulators for development and VOCs emission, thus promoting nutrient uptake and mycorrhizal function (Rana et al. 2012). Direct stimulation involves the synthesis of phytohormones like gibberellin, cytokinin, auxin, and biological nitrogen fixation, such as dissolving minerals, e.g., Fe and P, elevation of enzymes and siderophores, and systemic resistance. *Bacillus*, *Aspergillus*, *Trichoderma*, *Streptomyces*, *Pseudomonas*, and *Beauveria* are known strains as biological control agents for plants. The

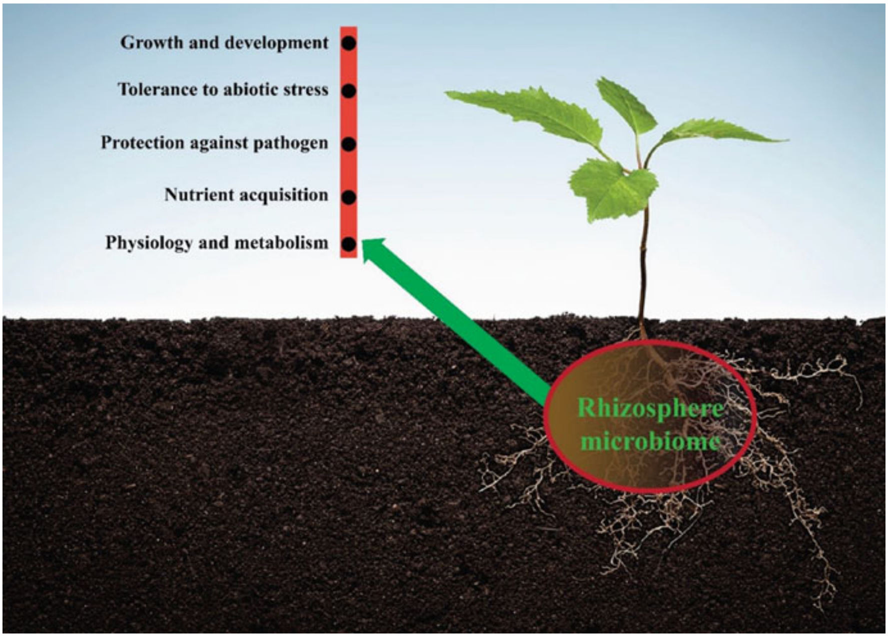

Fig. 12.2 Different functions of rhizosphere microbes in agriculture

mechanisms include their antagonistic activity, immunity, synthesis of elicitor molecules, and environmental stress. Another mechanism for crop control is phytoextraction (Rana et al. 2012). Phytoextraction utilizes minor element accumulation in plants which aggregates contaminants in the respective tissues or cells. Once the pollutants are absorbed, the plants can be removed by cutting. The process of phytoextraction can be developed through soil modification, which increases the accessibility of trace ingredients in the soil. The bacteria associated with the plant facilitate the accessibility of small components in rhizosphere, and this is one of the established defence mechanism and stress responses in the plant-bacterial colonization and interactions (Santhanam et al. 2014) which can be of great assistance in the phytoremediation of soils polluted with trace elements.

12.3.6 Different Types of Microbes

The microbial stimulation of plant growth can be attributed to the ability for biological N2 fixing, production of plant phytohormones e.g., gibberellic acids, indole acetic acid, and cytokinins; and biological control of phytopathogens by antifungal, antibiotic, anti-bacterial or, iron-chelating agents, induction of nutrient uptake, acquired resistance of host, and improved bioavailability of minerals (Verma et al. 2019; Suman et al. 2016a; Kour et al. 2017; Yadav et al. 2016a; Lottmann et al. 2000; Huang et al. 2009). Some of these bacteria also exhibit psychrotolerant characteristic (Verma et al. 2015). The efficiency of crop productions can be improved through the applications of microorganisms in agriculture (Table 12.1).

Utilizing N_2-fixing microorganisms as biofertilizers is among the most effective, eco-friendly, and favorable methods to improve the crop product and growth. The examples of N-fixing bacteria include *Azotobacter*, *Arthrobacter*, *Azospirillum*, *Enterobacter*, *Bacillus*, *Gluconacetobacter*, *Cerattia*, *Pseudomonas*, *Herbaspirillum*, and *Klebsiella* (Table 12.1) (Elbeltagy et al. 2001; Boddey et al. 2003; Wei et al. 2014). The PGPBs are also able to transform insoluble phosphorus into a soluble form (orthophosphate). Rhizospheric B-soluble microorganisms grown in symbiosis with rice, wheat, pulses, and maize could dissolve boron (B), the mineral critical for crop quality and yields, and these include *Azotobacter*, *Burkholderia*, *Arthrobacter*, *Halolamina*, *Enterobacter*, *Pantoea*, *Citrobacter*,

Table 12.1 Plant growth-promoting microbes for agricultural applications

Microbes	Response	Strain	Ref.
Azospirillum brasilense	Affected dry weight	Sp245	Turan et al. (2012)
Azospirillum brasilense	Coleoptiles growth	Sp245	Alvarez et al. (1996)
Azospirillum lipoferum	Alleviate drought stress	AZ1, AZ9, AZ45	Arzanesh et al. (2011)
Aeromonas vaga	Plant growth	BAM-77	Jha et al. (2013)
Aeromonas hydrophila	Plant growth	MAS-765	Ashraf et al. (2004)
Aeromonas vaga	Plant growth	BAM-77	Jha et al. (2013)
Achromobacter xylosoxidans	Plant growth	249	Barra et al. (2016)
Bacillus aryabhattai	Growth and yield	BCZ17	Verma et al. (2016)
Bacillus altitudinis	Growth and yield	BNW15	Verma et al. (2016)
Bacillus endophyticus	Growth and alleviate salinity	BNW9	Verma et al. (2016)
Bacillus amyloliquefaciens	Growth and alleviate salinity	IARI-HHS2–30	Mishra et al. (2011)
Bacillus alcalophilus	Plant growth	BCZ14	Verma et al. (2016)
Bacillus amyloliquefaciens	Growth and alleviate salinity	BNE12	Verma et al. (2016)
Cellulomonas turbata	Growth and yield	AS1	Ozdal et al. (2016)
Klebsiella **sp.**	Plant growth	SBP-8	Rana et al. (2016)
Micrococcus roseus	Growth and yield	SW1	Mahmood et al. (2016)
Paenibacillus xylanexedens	Growth and alleviate salinity	BNW24	Verma et al. (2016)
Planococcus salinarum	Growth and alleviate salinity	BSH13	Verma et al. (2016)
Pseudomonas fluorescens	Growth and alleviate salinity	153	Abbaspoor et al. (2009)
Pseudomonas putida	Plant growth	AKMP7	Ali et al. (2011)
Pseudomonas rhizosphaerae	Growth and alleviate salinity	IARI-DV-26	Verma et al. (2016)

Pseudomonas, and *Azotobacter* (Table 12.1) (Suman et al. 2016a; Gaba et al. 2017; Singh et al. 2016; Yadav et al. 2017a). The applications of phytase and phytospecific microorganisms also have great potentials (Kumar et al. 2013; Singh et al. 2014). The availability of adequate organic P (as phytate) in the soil enhances the importance of phytate-hydrolyzing microorganisms. The utilization of phytase-producing bacterial isolates (*Cellulosimicrobium* sp., *Advenella* sp., *Achromobacter* sp., *Bacillus* sp., and *Tetradios bacterial* sp.) result in enhanced plant growth. This is due to the synthesis of plant growth hormones and siderophores, solubility of P, and inhibition of plant pathogenic fungi (Kumar et al. 2013; Singh et al. 2014). These reduce the utilization of P fertilizers, thereby protecting the environment from P contamination and contributing towards sustainable agriculture. Excessive P could lead to serious environmental pollution in aquatic ecosystem (Kumar et al. 2015). Phytase-generating microbes or those phytases which are neutral furthermore can serve as the diet of aquatic organisms (Huang et al. 2009; Kumar et al. 2014).

These beneficial PGP microorganisms are capable of producing siderophores (iron-chelating substances), antibiotics, chitinases, different pigments having fluorescent properties, and HCN (Yadav et al. 2016a; Lottmann et al. 2000). Siderophore production by microbes inhibits the development of crop pathogens and introduces Fe to the crops. Siderophores have been associated with indirect and direct enhancement of plant growth by PGP microorganisms. Microorganisms with multifunctional PGP properties may be used as environment-friendly biological fertilizers (Verma et al. 2015, 2019; Suman et al. 2016a; Kour et al. 2017).

The salinity of soil is a major issue in a large number of fields, and the high concentration of salt causes soil infertility. Hypersaline soils are present in excess of saline soils and Na^+ – negatively charged clay particles. The growth of plants/crops is hindered by the higher levels of Na salt in soils. The accumulation of salts, e.g., NaCl, $CaCl_2$, and $MgCl_2$, happens constantly by the weather process (the rock is broken to release soluble salts). Beneficial microorganisms are linked to the roots of various plants with the help of root exudates. Epiphytic microorganisms are connected to the phyllosphere component of the plant because of the release of adhesive materials by the plants. Therefore, the interaction of plant microorganisms has been established, and the community of microbes has used elements of exudates as sources of energy (Yadav et al. 2015a, 2017b). Isolated microorganisms from growing crops in the high salinity/salty ecosystems possess the ability to promote plant development. Plant microorganisms that are rhizospheric, endophytic, and epiphytic have assisted in the growth of plant in vitro and in vivo, under osmotic pressure. Direct plant mechanisms through NH_3, HCN, siderophore (iron-sealing compounds), and other metabolites protect the plants from different pathogens and facilitate plant growth under harsh environment (Singh et al. 2016; Verma et al. 2016; Yadav et al. 2015a, 2017c) (Table 12.2).

While halotolerant/halophilic bacteria bacteria may enhance the growth of plant based on increased multifunctional PGP properties, biofertilizers improve germination, length of shoots and roots, biomass, and N_2, for higher yields and increased NPK (nitrogen, phosphorus, potassium) contents, chlorophyll content, and soil protein, and elevate tolerance to salinity (Yadav et al. 2015b, 2017c, d, 2018a;

Kumar et al. 2016, 2017; Verma et al. 2013, 2015; Vazquez et al. 2000; Kaur et al. 2017; Suman et al. 2016b; Yadav 2015).

Table 12.2 Halophilic microbes for agricultural applications under saline environment

Microbes	Response	Strain	Ref.
Aeromonas hydrophila	Growth and alleviate salinity	MAS-765	Ashraf et al. (2004)
Arthrobacter sp.	Salt stress and growth	AS 18	Tiwari et al. (2011)
Azotobacter chroococcum	Alleviated salinity	C5	Rojas-Tapias et al. (2012)
Aeromonas vaga	Plant growth	BAM-77	Jha et al. (2013)
Bacillus insolitus	Growth and alleviate salinity	MAS 17	Ashraf et al. (2004)
Bacillus sp.	Growth and alleviate salinity	MAS 617	Ashraf et al. (2004)
Bacillus licheniformis	Nutrient uptakes	RS656	Siddikee et al. (2011)
Brevibacterium iodinum	Nutrient uptakes	RS16	Siddikee et al. (2011)
Bacillus amyloliquefaciens	Salt tolerance	SN13	Nautiyal et al. (2013)
Bacillus aquimaris	Alleviated salinity	DY-3	Li and Jiang (2017)
Chryseobacterium gleum	Nutrient uptakes	SUK	Bhise et al. (2017)
Enterobacter sp.	Plant growth	12	Barra et al. (2016)
Enterobacter cloacae	Root growth	PD-P6	Yaish et al. (2015)
Kocuria erythromyxa	Alleviated salinity	EY43	Yildirim et al. (2008)
Nitrinicolalacis aponensis	Salt growth stress	SL11	Tiwari et al. (2011)
Pseudomonas putida	Plant growth	TSAU1	Egamberdieva and Kucharova (2009)
Pseudomonas fluorescens	Plant growth	YsS6	Ali et al. (2014)
Paenibacillus xylanexedens	Root growth	PD-R6	Yaish et al. (2015)
Pseudomonas aurantiaca	Growth and alleviate salinity	TSAU22	Egamberdieva and Kucharova (2009)
Pseudomonas extremorientalis	Growth and alleviate salinity	TSAU20	Egamberdieva and Kucharova (2009)
Pseudomonas fluorescens	Plant growth	153	Abbaspoor et al. (2009)
Pseudomonas chlororaphis	Growth and alleviate salinity	TSAU13	Egamberdieva and Kucharova (2009)
Pseudomonas extremorientalis	Growth and alleviate salinity	TSAU6	Egamberdieva and Kucharova (2009)
Planomicrobium okeanokoites	Growth and alleviate salinity	BNE8	Verma et al. (2016)
Xanthomonadales sp.	Plant growth	CSE-34	Piernik et al. (2017)
Zhihengliuela alba	Nutrient uptake	RS111	Siddikee et al. (2011)

Plant microorganisms produce hormones that regulate plant growth, such as cytokinins, IAA (indole acetic acids), and gibberellic acids. The production of IAA is the most abundant and is synthesized by plant-microbial interactions, for example, endophytic, epiphytic, and rhizosphere microorganisms. Gibberellic acids are also common hormones produced by rhizosphere microorganisms, while the synthesis of cytokinins is possible by liposphere/epiphytic microorganisms. The synthesis of growth regulators by various groups of microorganisms gives many benefits to plants, e.g., growth of root, absorption of water, and the uptake of nutrients from soil-to-plant, and enhances stress tolerance, e.g., heat, cold, dryness, as well as salinity (Yadav 2015; Verma et al. 2014; Yadav et al. 2018b; Suman et al. 2015). Microorganisms with the 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase activity could reduce ethylene levels during high salinity. These include *Bacillus*, *Arthrobacter*, *Bicriteria*, *Methylobacterium*, *Phenazacillin*, *Enterobacter*, *Pantoja*, *Pseudomonas*, *Penicillium*, *Rhizobium*, *Rhizobacteria*, and *Cerattia* (Yadav et al. 2018b; Glick 2020). Plant microorganisms may also involve indirectly in the PGP activities with the production of NH_3, HCN, siderophore (iron-chelating compounds), antimicrobial products, pigments, antibiotics, and hydrolytic enzymes chitinases, (β-1, 3),-glucanase, pectinases, and cellulases (Yadav et al. 2016a, b; Verma et al. 2016). These properties and characteristics play their role in protecting plant crops from different kinds of pathogens of plant, and the use of such microorganisms as biofertilizers may enhance the crop productivity (Verma et al. 2018). The most efficient and excellent microorganisms that increase the growth of plant via direct mechanisms of PGP are *Aeromonas*, *Bacillus*, *Photobacterium*, *Enterobacter*, *Pseudomonas*, *Trichoderma*, and *Xanthomonas*. The utilization of microorganisms as biofertilizers as a substitute to chemical fertilizers improve soil health and promote green agriculture. Rhizospheric microorganisms basically make colonies in the roots and stimulate plant growth under natural and saline environment. Halophilic microorganisms contribute to the development plants via different PGP activities even under salinity (Verma et al. 2013, 2014, 2016; Kumar et al. 2017; Yadav et al. 2018b).

12.4 Healthy Soil and Eco-Friendly Environment

Seed treatments in the form of microbial vaccines transport microbes straight into the rhizosphere of plant, with narrow soil areas surrounding the roots where plants directly interact with the microbes (Philippot et al. 2013). This is an area where intensive microbial activity occurs that depends on the growth of microbes and the availability of nutrients and other molecules, e.g., antibiotics and plant growth regulators. The rhizosphere colonizing species are beneficial microbes that have major role in agriculture with the potential to enhance plant growth through different mechanisms (Babalola et al. 2009).

12.4.1 Biofertilizers

Microorganisms in the soil help to improve productivity of agriculture. The naturally available living organisms are biofertilizers and biopesticides to help the growth of plant and overcome pests, weeds, and diseases. Friendly microbes help plants in the absorption of higher quantity of nutrients through. “Nutrient recycling” and “capture” the energy needed. In return, the waste by-products of the plants serve as food to the microbes. As excessive utilization of chemical fertilizers to meet the demand for agricultural products is one of the major reason for environmental pollution, biological fertilizers are increasingly seen as the antidote. Advantages of biofertilizers are illustrated in Fig. 12.3. Soil bacteria and specific types of fungi known as phosphorus-soluble microorganisms (PSMs) could convert insoluble forms of phosphates into solvable forms of phosphates by releasing organic acids (Meena et al. 2016). The soil pH is decreased by these acids. *Rhizobium*, blue-green algae (BGA), and *Azolla* are considered plant-specific biofertilizers, while *Azospirillum*, *Azotobacter*, Vesicular Arbuscular Mycorrhiza (VAM), and phosphorus soluble bacteria (PSB) are broad-spectrum biofertilizers (Gupta 2004; Teotia et al. 2016).

The major sources of biofertilizers are fungi, bacteria, and cyanobacteria. Other soil bacteria (*Azospirillum* and *Azotobacter*) can fix atmospheric nitrogen, thereby enriching the nitrogen content in the soil through the symbiotic interaction with the plants. *Glomus* is a genus of arbuscular mycorrhizal (AM) fungi. Plants which interact with the VAM exhibit improved nutrient uptake such as the P uptake, tolerance to root-burn pathogens, drought and salinity, and overall improvement in the plant development. Autotrophic microbes, i.e., Cyanobacteria, found in terrestrial and aquatic ecosystems, may retrieve N2, and the blue-green algae help to add

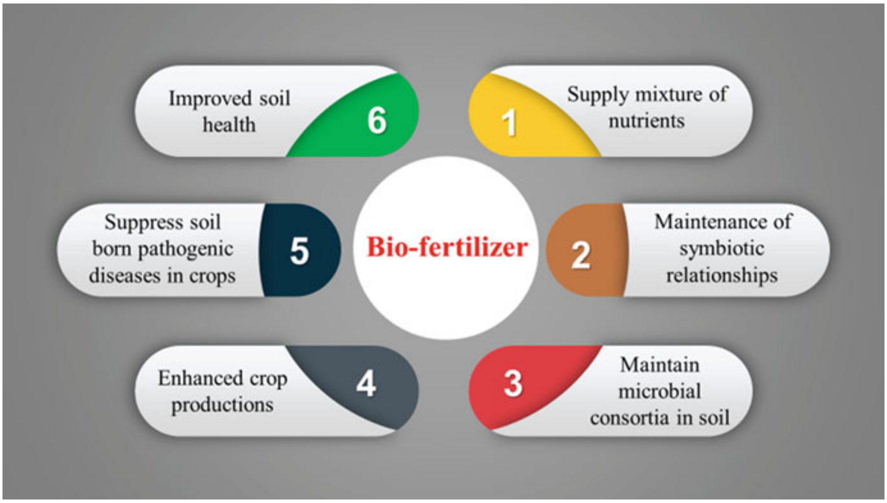

Fig. 12.3 Benefits of biofertilizers in agriculture

organic matter into the soil and enhance its productivity. Phosphate (PO_4^{-3}) and N_2 are significant for the development of plant, and both are easily available from natural resources. PO_4^{-3} has a significant role, directly or indirectly, during plant maturity, for N_2 fixation and for the quality and yield of the crop. A fungus such as *Penicillium bile* produces organic compound with acidic properties, to help in the dissolution of PO_4^{-3} from the soil, which eventually reaches the soil for the absorption by the plant roots. *Rhizobium* which reside in nodules on the roots of the plant are involved in the extraction of N_2 from air and conversion of nitrogen into a usable organic form. Those plants which possess larger populations of friendly bacteria residing in their roots can utilize naturally occurring nitrogen instead of depending on expensive fertilizers. Biofertilizers assist the plants in the utilization of all the nutrients present in the air and soil, and this finally lead to the reduction of the quantity of chemical fertilizers utilized.

12.4.2 Biopesticides

Biopesticides are obtained from natural sources, e.g., plants, animals, bacteria, and certain minerals. These sources can be fungi, e.g., *Bavaria* sp., neem extract, *Bacillus* sp., and pheromones. Baking soda, canola oil, bacteria, fungi, viruses, protozoa, nematodes, and other biologically active, safe substances are all considered as biopesticides, if they are used to control pests in eco-friendly manner. The advantages include for efficient control of pests, plant weeds, and diseases along with environmental and human protection. Biopesticides have found significant application in those areas facing pesticide resistance, and environmental concerns, and in the niche markets aiming to reduce the utilization of chemical pesticides (Mazid et al. 2011). The most commonly known microbes are *Bacillus thuringiensis* (BT), which produce a protein that may kill specific pests or insects in potatoes, cabbage, and other crops. The basic requirement is that the biopesticide only kills the target organisms but not the non-targetted ones or humans. Plant growth-promoting rhizobacteria (PGPR) are functionally diversified bacterial groups that possess higher capability as biopesticides and biofertilizers. They are cost-friendly and eco-friendly substitutes to chemical fertilizers or other synthetic counterparts (Mazid et al. 2011). Some microorganisms which are pathogenic to plants can be genetically-modified to control pests and weeds. The best example is BT which has been successfully utilized as a specific, safe, and effective tool for insect pest control (Roh et al. 2007). BT is effective against Black flies and mosquitoe larvae, but may be harmful to moths and butterfly caterpillars larvae. The target insect species determine whether a certain BT type synthesizes a protein that binds to a gut receptor of larvae or merely by starving the larvae (Kumar et al. 2008).

Microbial pesticides as biological control agents are safe as compared to other conventional synthetic pesticides (Buss and Park-Brown 2002). The formulas (inoculants) of seed coating make use of adventitious organisms to safeguard the seedlings. Biopesticides have a short life span and, unlike synthetic pesticides, do not have harmful effects on animals and ecosystems, as they are super selective with specific targets of the class/type of insect. Traditional pesticide sprays, such as dust, liquid drains, liquid concentrations, wet powders, or granules, are used and the specific feature of each product determines the most effective ways for delivery of agents to the target pests (Nicholson 2007).

The rod-shaped bacteria are the bacterial pathogens of the Bacillus used for pest control and they usually reside in soil. The products with *Bacillus thuringiensis* Kurstaki destroy a variety of kite caterpillars and butterflies. In contrast, *Bacillus papillae* (milky spore disease) destroys the larvae of Japanese beetle, but it shows no response against the annual white grub (*Cyclocephala* mask), which is usually associated with pasture. BT has been the most commonly used microbial pesticide in the United States since the 1960s. BT products are commercially manufactured in huge industrial fermentation tanks. When the bacteria survive and reproduce under optimal conditions, the cells synthesize spores and toxic crystalline protein known as endotoxin. Most existing commercial BT products consist of toxic proteins and spores, but only a few toxin fractions can be cultured (Mueller and Sachs 2015; Singh and Trivedi 2017). Pesticides marketed under the trade names Zapidemic, Doom, Grub Attack, and the common name "milky spore disease" consists of *Bacillus papilla* and *Bacillus lentimorbus*.

The production and utilization of pesticides based on virus is limited. In contrast to BT, the living host insects must produce the insect viruses. Therefore, the product is expensive, time-consuming and less efficient as compared to the already present synthetic chemical pesticides. However, many insect viruses are related to the same species or pests of the forest, such as the gypsy moth, spruce budworm, Douglas-fir tusk moth, and Pine sawdust. They are not attainable commercially, but they are being prepared and utilized by the Forest Services of the United States. Forest pests are specifically better targets to be attacked by viral pathogens as the stability of the forest environment takes an important part in the cycling of pathogen (transmitted from one generation to another). Forest canopy have a significant part in the protection of viral cells from being destroyed by UV radiation. Baculovirus affects pests such as corn bores, flea beetles, potato beetles, and aphids (Berendsen et al. 2012). A special breed is employed as an agent to control the bertha army worm, which attacks flax, canola, and other vegetable crops. Traditional pesticides have no effect on the worm until it reaches a point when there has been extensive damage. Other pest viruses tested for use as pesticides include alfalfa looper, armyworm, soybean looper, imported cabbage, and cabbage looper. However, few of these viruses are manufactured and trialed in the fields and none of them has been recorded or marketed in a commercial manner. Both the cooling moth GV and the Heliothis nuclear polyhedrosis virus (NPV) are simultaneously registered and commercially produced by the US EPA, but these items are no longer attainable.

A large number of insect hosts are naturally infected by protozoan pathogens. Although these pathogens destroy their host insects, they are necessary for their long-term impacts. A significant and general result of the infection of protozoa is the reduction in the number of organisms produced by affected insects. Although pathogens of protozoa possess an important character in the natural population, some pesticides appear to favor development. The species in genera *Nosema* and

Vairimorpha have potentials as insecticides (Weinzierl et al. 1995). The pathogens invade the larvae of the lepidopterans and insects of the Orthoptera (grasshopper and related pests). Protozoan microsporidian is currently available for the manufacturing of registered pesticides. Microbial pesticides offer protection for animals and humans because they are essentially non-toxic and non-pathogenic. Many of the microbial pesticides produce significant effects against narrow range of pest types, and because these pesticides are likely to deactivate rapidly in the environment, consumers should select the pest targets and the formulation having the most efficient and effective application.

12.4.3 Bioherbicides

Weeds are competing with crops for water, sunlight, nutrients, and space, as well as block drainage and irrigation systems, leading to poor quality of crop with deposit of weed seeds in the harvest. Weeds can be controlled by bioherbicides. Bioherbicide utilization, in place of chemical herbicides, lead to an increasingly successful strategies of integrated management (Hoagland 2007). Bioherbicides include phytopathogenic microorganisms or microbial compounds that can be used for the control of weed. Many microorganisms and phytopathogenic bacteria and fungi have bio-herbicidal functionality, and have been described in patents as the agents of weed control. The phytotoxic constituents of many chemical agents as well as other secondary compounds produced by such pathogens may also be poisonous to other mammals. In addition, the translocation, intake, metabolism, and persistence of these phytotoxins and the environmental impacts of increased chemical herbicide applications to other microbial communities are not well-understood. Microbes may contain aggressive genes which may invade the defence genes of weed, thus ultimately leading to death. The advantage of using bioherbicides is that it stays for longer period in the environment during the season of growth. It is cost-effective as compared to synthetic herbicides, so it can decrease the cost of cultivation. In addition, bioherbicide is not dangerous to the environment and does not affect non-target organisms (Singh et al. 2006).

12.4.4 Bioinsecticides

Similar to viruses, fungi sometimes behave as significant agents to control and inhibit the population of insect. Most of the species which create infections in insect are dispersed by the spores of conidia known as conidiophores. The conidia spread from different fungi possess different capability and the germination requires high humidity or free water. Contrary to bacterial spores or virus cells, the conidia of fungal spores originating from the cuticle synthesizes specific structures which can invade and enter the body of the insect. As the fungal infection grows, the toxins kill the infected insects. The advantage is the fungus are not killed by the long-term effects of the parasites (Berendsen et al. 2012). The fungus causes diseases in about fields and none of them has been recorded or marketed in a used as bioinsecticides. Techniques involving fermentation are employed for mass production of fungi. Spores are packed so that they may be spread to areas where the insects can be infected. After plantation, the spores utilize enzymes to enter the insect body. Once injected into the insect, they start to reproduce and ultimately lead to the insect death. Fungal agents have been recommended to have the best potential for chronic pest control. The biological pesticides attack in multiple ways, that the plant resistance to pests may be much increased.

12.5 Microbiome and Sustainable Agriculture

The aim of sustainable agriculture is to achieve high productivity of animals and plants through economical approach, making use of flexible and adaptable technology, with minimum disturbance to the environment. It needs to address the negative impacts of agrochemicals (pesticides, mineral fertilizers) with the applications of symbiotic microbes that facilitate nutrient supply to the livestock and crops, and provide control against biohazards (pests, pathogens) and abiotic stressors (including climate fluctuation and pollution) (Yang et al. 2009). This highlights the significance of microorganisms with respect to sustainable agro-practices and health of environment (Wang et al. 2009). This is attributable to the genetic dependence of the plants on the symbiotic interactions with the surroundings. The potential of plant-microbial symbiosis extends beyond the environmental impacts, as it also involves nitrogen fixation (Franche et al. 2009) and the molecular and ecological processes with multiple pathways for mutual co-evolution and adaptation of the microbes and the plants (Arnold et al. 2010). For the fungi-plant interactions, the host genotype is an important parameter for the spreading of fungal component (mycobionts) and for the development of the specificist-mutualist and specio-genetic continuum interactions (Peay et al. 2010). In the case of leguminous crops, highly active rhizobia strains can be utilized to provide nodulation to support N_2 fixation for sufficient symbiotrophic nitrogen nutrition, using moderate levels of N-fertilizer (Provorov and Tikhonovich 2003). Maximum productivity can be attained by considering the species-specific and genotype-specific types of nutrition (Provorov et al. 1998). The use of beneficial microbes in agro-practices could reduce the use of inorganic fertilizers, water, pesticides and herbicides, without affecting the crop yield (Andrews et al. 2010). Intact tropical forests have been reported to accumulate and recycle higher quantities of N than the temperate forests, attributable to the abundance of N-fixing plants and sustained transport of bioavailable N within the ecosystem (Hedin et al. 2005). The optimal nutrients should lead to efficient formation of the colonies within the host, and the symbiosis can be enhanced according to the specificity of the host (Provorov and Vorobyov 2009). Microbial symbionts or their derivatives represent a promising area for sustainable agricultural technology for plant development and protection. Future prospects of microbial applications include the production of novel multipartite ecto- and endosymbiotic interactions which are based on extensive molecular (metagenomic) and genetic investigation. The basic strategy is to prepare composite inoculants that mimic the microbial communities linked to the natural plants. To balance plant-host metabolism, a combination of P- and N-providing sebum, including endosymbiotic rhizobia + VAM-fungi, appears promising. Some of the issues are related to the opportunistic or common pathogens of humans, which are often present in endophytic communities, including *Klebsiella*, *Escherichia*, *Salmonella*, *Enterobacter*, and *Staphylococcus* species (Shtark et al. 2010; Ryan et al. 2008). Productive handling of symbiotic communities of microbes is possible by utilizing molecular tools based on the pools of microbes that constantly migrate between soil, animal, and plant bodies in agricultural and natural ecosystems (Kupriyanov et al. 2010).

A few bacteria, e.g., agro-bacteria and rhizobia, are employed to deliver seed inoculants to the plants. The importance of microorganisms such as *Azoarcus* sp. to plants is that it serves as grass endophyte (Hurek and Hurek 2003). These types of bacteria mostly support rice crops and they do not harm the environment. After the seeds are sown in the soil, there is a significant role of bacteria in its germination. The bacteria thrive in the seed, which feeds them. Bacteria enhance soil fertility by providing nutrients for plant growth. They assist in food softening in the seeds, which facilitate the plants to grow from the seeds. Bacteria not only play significant part in the early stages of plant development, but also provide protection against pests and tolerance against stressors such as drought (Parke et al. 1983).

12.5.1 Benefits of Mycorrhizal Fungi

Growth of mycorrhizal plants could tolerate adverse conditions such as drought (Parke et al. 1983), soil pathogens, transplantation, poor soil nutrient, and soil contamination (Leyval et al. 1997). Improvement in plant growth and enhanced resistance to unfavorable conditions is often associated with the increased nutrient and water uptake, which is feasible through comprehensive hyphal networks with enhanced root area for assimilation. The impact of mycorrhizal fungi on the plant development, as illustrated in Fig. 12.4, includes enhanced root system growth and improved nutrient/water absorption and utilization. In *Eucalyptus globulus*, the dry weight of the plant is associated positively with the extent of mycorrhiza-colonized root. The benefits of ectomycorrhiza become more apparent in the establishment and development of young transplants in horticulture and forest care (Munro et al. 1999; Scagel and Linderman 1998).

The mycorrhizal symbiosis could improve phosphorus content through a wide range of hypercellular networks. This permits plant root to cross the phosphorus depletion area and reach a stable phosphorus-rich area where the fungus dissolves. Phosphorus, in many cases, can compensate for the effect of mycorrhizal infection on the plant survival under mycorrhizal control. However, increased P content may also lead to reduced mycorrhizal infection. Generally, the beneficial effects of mycorrhiza on the plants disappear as a result of excessive supply of phosphorus. The application of stimulants in conventional agriculture has often overlooked the beneficial symbiotic activity of mycorrhizal fungi (Jacott et al. 2020).

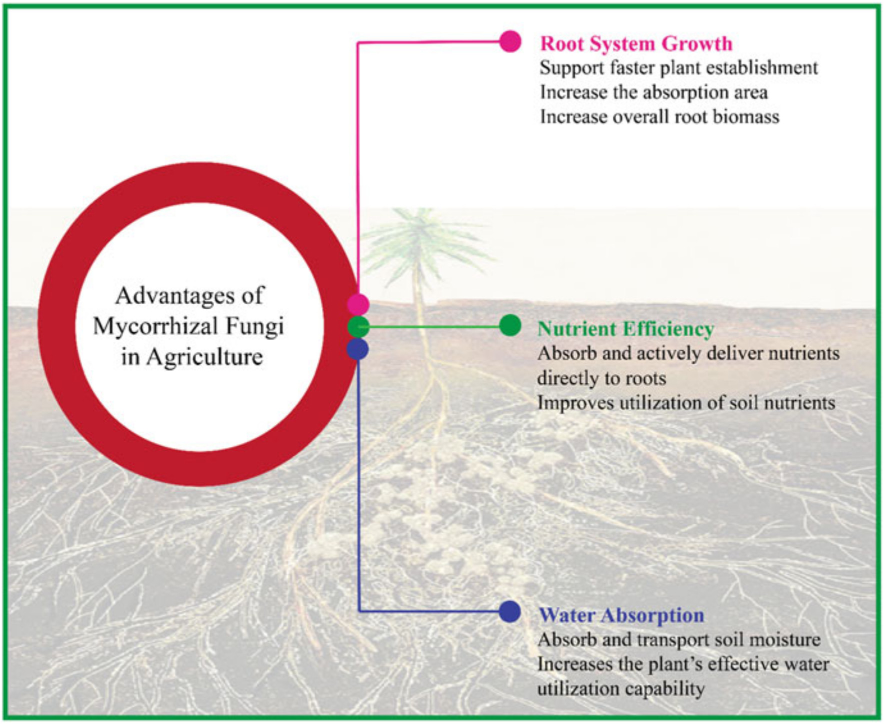

Fig. 12.4 Advantages of mycorrhizal fungi in agriculture

12.5.2 Soil and Environmental Health

Certain communities of microbes influence plant physiology, rhizome, and nutrient soil physiochemical properties directly or indirectly through metabolism. PGPR are the significant constituents of integrated farming, helping in nourishing crops with essential nutrients, and help to address the uptake of atmospheric nitrogen; the soluble and aggregated phosphorus; and the conversion microelements such as Mo, Zn, Cu, etc. into plant constituents. The production of hormones that promote plant development, such as indole acetic acid and gibberellic acid and polysaccharides, helps to improve the soil structure, thereby improving the soil health and increase the crop production. The amount of nutrients like K, Zn, Ca, Fe, Mn, and Cu can be improved by the proton pump ATPase (Mantelin and Touraine 2004). There are many reports on the importance of PGPR in maintaining soil fertility (Singh et al. 2018). PGPR vaccination of seeds has improved the value of accessible phosphorus, populations of microbes, acid and alkaline phosphate, dehydrogenase activity in soil, and high yields from irrigated seeds (Hemashenpagam and Selvaraj 2011).

The problems and solutions for healthy environment through the management of microorganisms can be achieved by combining the understanding in environmental biotechnology with microbial ecology (Damjanovic et al. 2017), to improve the quality of the environment, safety, sustainability, and human health (Umesha et al. 2018). The molecular biology tools based on polymerase chain reaction (PCR) amplification and microbial DNA development can detect the identity and function of individual microbes. The latest technologies on high-throughput genetic and proteomic techniques could identify particular genes along with their metabolic activities. The whole genome of microbes which is once "unusable" can now be reconstituted utilizing current advancements in biology, computing, materials, and engineering. The focus has now shifted to the use of communities of microbes (Demain 2000), for bioremediation of polluted water, sludge, sewage, and sediment; or for soil detoxification; or for extraction of renewable energy from biomass, pathogens, or contaminants, while reducing their hazardous effects.

12.6 Conclusion

The application of commercial fertilizers and synthetic chemicals as pesticides have improved the crop yield, but with equally huge impact on the environment from the polluted and contaminated ecosystems. The growing concern over food safety has led to the development of more eco-friendly techniques, moving away from the toxic synthetic chemicals. Exploiting the links between soil microbial communities and the crops is the right approach to increase food production at low environmental cost while meeting the demand of growing world population. The two main strategies in the management of the soil microbes are based on the development of microbial vaccines or dealing with naturally occurring microbial populations. There has been an increasing interest in the use of biofertilizers, biopesticides, bioherbicides, and bioinsecticides to improve the crop quality and yield. The improvement of plant-microbial symbiotic relationships involve the extent of biocontrol exerted by the microbes, optimal microbial communities, soil modifications, and the types of soil and crops. Microbiological technologies, sustainable approaches, and improvement in regulatory framework could lead the way for emerging microbial-based solutions and new agro-practices with increased productivity.

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