Chapter 3

Role of Microbes for Attaining Enhanced Food Crop Production

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Abstract The global production of food crops is on increase but the perpetual accrual of demographic strain has posed a challenge toward the attainment of global food security. In spite of covering several milestones in enhancing global food production, in a total of 821 million people, one out of nine still sleeps with an empty stomach each night, and one in three has to face the evil of malnutrition. Comprehensively, the world hunger is appraised to have augmented since 2014, as assessed in terms of both percentage and the absolute number of population. Unambiguously, Africa had the highest prevalence of undernourishment, representing 27.4% of its entire population, whereas Asia accounts for 64% of the total malnourished people across the world. Surprisingly, India also serves as a home to one-fourth of all malnourished people worldwide, which makes this country a key focus for confronting the hunger on an international scale. Therefore, in a quest to increase food production, microbes can play tremendous role due to their various incredible potentials. The microflora associated with plants have fabulous potential to improve plant resilience and produce in farming systems. The judicial employment of microbes or their metabolites can heighten nutrient uptake and yield, control pests, and mitigate plant stress responses. The unhidden potential of microbes makes them potent biocontrol agents and promotes their application as biofertilizers and their role as agents for improving soil health along with their plant growth promotion attributes that warrant their employment in agroecosystems for enhancing crop production. Therefore, the present review targets different stratagems which advocate the role of microbes for enhancing the quality and quantity of the produce.

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3.1 Introduction

The realm of agriculture has to confront an expansive gamut of challenges of climatic changes, stagnant crop yield, nutrient deficiency and deterioration of soil organic matter, availability of water and dwindling of cultivable land, increasing resistance toward GMOs, and paucity of labor. Moreover, the distress of lassitude instigated by the doings of green revolution is still being suffered by the agricultural systems. The reckless fertilizer applications in the last five decades has tremendously augmented from 0.5 tons to 23 million tons in a period of time from 1960 to 2008. Although the explicit usage of chemical fertilizers has resulted in a tremendous increase of around four times in the output of food grains, the continuous decline in the organic content of the soil due to this unchecked fertilization has also resulted in a stagnant yield of certain crops (Pandey 2018). In addition to it, the degradation of land is also promoted by a number of natural as well as anthropogenic activities including the declined fertility of soil, loss of soil organic matter, erosion, and the harmful consequence of toxic chemicals. Thus, all these deeds are posing a grave threat to the global environmental status (DeFries et al. 2012). Moreover, the food system of the present world is also facing severe challenges pertaining to environmental sustainability such as biodiversity loss, climate change, food insecurity, and water scarcity (Bilali and Allahyari 2018). The perpetual increase in the human population which further leads to a subsequent increase in the global consumption of food thus leads to an increase in the demand for affordable productive lands. The 2018 Global Hunger Index (GHI) report ranks India 103rd out of the 119 countries. The score of India is 31.1 which clearly denotes the serious hunger levels in the country. The country has the 17th highest hunger levels indicating alarming levels which has raised the food safety concerns. Therefore, there is a dire need to prevent any further degradation of such lands, and the restoration of the earlier degraded lands is also seeming to be extremely important. Moreover, it is quite unblemished that the development of orthodox agricultural habits in order to meet the future food loads is neither parsimoniously nor ecologically feasible. There should be involvement and implementation of the sustainable practices of land use along with the restoration as well as protection of the deteriorated or marginal soils for safeguarding the food security for this growing population demand (Ahmad et al. 2018). The global hunger has enlarged after nearly a decade of sustained waning. The population of malnourished people has augmented surprisingly from 777 million to 815 million from 2015 to 2016, respectively, on a worldwide basis. The global prevalence of stunt growth among children below five years of age is still 23% which accounts for 155 million children worldwide. The projection of current trends will lead to stunting of around 130 million children in 2025 which is 30 million above the World Health Assembly target (FAO 2017). The exertions required to combat the hunger and malnutrition in a sustainable way will be governed by restructuring the food systems. Thus, a number of such problems can be fixed by food, but such processes require the reshaping of food systems for health, inclusion, and nutrition along with the environmental sustainability (IFPRI 2018). In this regard, the development in agricultural sector is perceived as an obligation to fight food insecurity confronted by numerous agricultural families (Goshu et al. 2013). Therefore, the quest of this modern era is a sustainability transition. In agriculture, the perception of sustainability transition appertains to a swing from a system that is strictly focusing on enhancing productivity called as agri-food system to another system which is solely put together around the extensive ideologies of sustainable agriculture (Brunori et al. 2013). Thus, in order to upsurge the food security, the vital factor is the maintenance of soil fertility and sophisticated food productivity with admiration to the ecological challenges (Nkomoki et al. 2018). Thus, the present era accentuates the dire role of adoption of eco-friendly and sustainable agricultural practices in order to uphold the soil fertility as well as productivity.

An outsized fraction of various organisms in the terrestrial bionetworks reside underneath the ground in soils and are supposed to play an important part in the ecosystem services (Prashar et al. 2014). The engagement of such microorganisms seems to be a viable approach for uplifting the status of modern agriculture in terms of advocation of environmental sustainability as well as for enhancing the production efficacy. The plant-allied microbiota have an incredible capability of improving the plant resilience as well as produces in agricultural systems. There is accumulative indication that biological technologies employing microbes or their metabolites can augment the nutrient uptake and yield, check the pest dynamics, and also alleviate the plant stress responses along with the promotion of resistance toward disease in plants (Trivedi et al. 2017). Plants have evolved into a world of microbes. The most primitive plants stretched their roots into primeval soil where they come across a territory already crowded with bacterial as well as fungal life (Heckman et al. 2001). From the very first day, plants probably started prompting the rhizospheric microbiota. In fact, plants engineer their own rhizospheric environs by discharging explicit exudates so as to advance nutrient accessibility and to interact with definite advantageous microbes (Liu et al. 2016). Surprisingly, the furthermost primitive plant lines also display their sturdy ability to modify the comparative lavishness of diverse microbial groups in the soils neighboring the rhizospheric portion (Valverde et al. 2016). The microbial group supported by different plant species is found to be precise as well as unique (Gertsson and Alsanius 2001). These distinct microbiomes have been accredited as a result of variances in the chemistry of root exudates (Rasmann and Turlings 2016) and in plant nutrient uptake rates (Bell et al. 2015). There are also leading evidences that soil microbiomes have the ability of acclimatizing to their particular crops over time which results in improved plant–microbe dealings (Berendsen et al. 2012). This approach of engineering the microbiome which is greatly host-facilitated picks out the microbial groups ultimately through the host and controls host behaviors that developed to impact microbiomes. The approach of increasing the plant fitness coupled with the elevated yields by artificially selecting upon microbiomes and consequently engineering advanced microbes with specific effects on the plants has been anticipated (Mueller and Sachs 2015). Similarly, optimized microbiota that aid the plants to develop early or flower later may perhaps be employed as inoculants for conferring drought resistance since plants are acknowledged to implement transformed flowering time in reaction to numerous abiotic stresses (Kazan and Lyons 2015). The process of engendering the host-facilitated artificial selection of microbes seems to be an inexpensive method to curb plant ailments instead of the reckless application of different pesticides as well as antibiotics, or creating genetically modified organisms. Moreover, different discoveries on the overlying "functional core microbiome" in different plant species provide strong support for cross-compatibility of microbiome transfer with phylogenetically unrelated plant species (Trivedi et al. 2017). Therefore, the different lucrative beneficial attributes of the microbes make them superior agents for improving the crop yields. They benefit the plants in numerous ways. Microbes are largely involved in upsurging the nutrient mobilization, thereby augmenting the nutrient consumption efficiency of the plants. They also have several indirect beneficial attributes like they encourage the plant growth in an indirect way by averting the growth as well as activity of pathogens. Microbes are also directly involved in the growth promotion, for example, by fabrication of phytohormones. There has been a large body of literature describing potential uses of plant-associated bacteria as agents stimulating plant growth and managing soil and plant fitness (Welbaum et al. 2004). Such beneficial microbes can be judiciously employed for increasing the growth of crop plants in order to get increased yields for feeding this ever-increasing population. Therefore, the chapter largely focuses on the different beneficial attributes of microorganisms which make them superior agents for attaining heightened crop production.

3.2 Microbes as Agents for Soil Rejuvenation

The three-dimensional natural body on the Earth's surface is designated as soil which is considered to be of utmost significance to several ecosystem occupations comprising biomass production and net primary productivity, climate temperance, water purification, biodegradation of toxic pollutants, storage of water and plant nutrients, and recycling of elements (Lal 2009). Soil is the foundation of agricultural as well as of natural plant populations; thus, it is the core of all the terrestrial life forms. The tinny sheet of soil casing the Earth's surface characterizes the variance amid survival and annihilation for most land-based life. Nevertheless, records of productive aptitude of soil point toward human-induced deprivation on almost 40% of the global agronomic land as an outcome of soil erosion, atmospheric pollution, widespread soil cultivation, overgrazing, land clearing, salinization, and desertification. To be sure, the deprivation coupled with damage of fruitful farming land is among the demanding environmental trepidations, outdone only by the man-made environmental complications, for instance, global climate change, depletion of the protective ozone layer, and grave deteriorations in soil biodiversity (Doran and Zeiss 2000). The theatrical intensification in the usage of chemical fertilizers in the quest of attaining optimal harvests has greatly become a fundamental constituent of the current agronomic practices. Such a recurrent and unnecessary application not only is lavish but also deteriorates the environs at a very quick frequency and thereby turns the soils incongruous for agriculture. Additionally, the soil deterioration, instabilities in configuration coupled with the practical possessions of soil microbial populations, and, subsequently, forfeiture of the soil fertility following different soil management performs have further added to the agronomic difficulties (Khan et al. 2009). The dreadful conditions of soil also have a very strong effect on human nutrition as well as health due to its hostile influences on the quality as well as quantity food production. The perpetual reduction in the harvests and agronomic fabrication intensify the food timidity that at present distresses around 854 million people internationally, and the truncated level of protein as well as of micronutrients exacerbates undernourishment and concealed hunger that touches 3.7 billion individuals, specifically children (Lal 2009). Therefore, in order to mitigate such detrimental deeds, mankind is in a dire need of a viable alternate that could have the potential to address the prevailing glitches in a more effective way and in a sustained manner too. Thus, the microbiological approaches incorporating the employment of functionally varied microbial communities as the vivacious constituents of soil ecosystems offer an economically viable option (Khan et al. 2009) for improving soil health as well as soil quality.

Soil health may be defined as the capability of the soil to function as a vigorous living organization, within the ecosystem and land-use frontiers, to withstand plant as well as animal production, preserve or augment air and water quality, and encourage plant and animal health. Soil quality, on the other hand, denotes the aptitude of the soil to accomplish numerous of these ecosystem purposes. On the contrary, soil deterioration indicates reduction in the quality and capability of the soil as a result of natural or anthropogenic perturbations. It can also be stated that soil degradation is the reduction of soil's current or prospective aptitude of performing several ecosystem functions, conspicuously the food, feed, and fiber production as an outcome of one or more deprivation progressions. The chief degradation processes comprise physical, chemical, and biological changes in the soil (Lal 1993, 1997).

The services that play a key role in shaping the rhizospheric microbial populations cannot be entirely understood without discussing their impacts on the soil surroundings. The diversity of soil ecosystems can be assumed by the fact that a gram of soil is a home for around 10,000–50,000 microbial species (Schloss and Handelsman 2006). The unique bacterial as well as fungal groups are found to be allied with soils of variable texture (Frey et al. 2004) and variable nutrient composition (Chaparro et al. 2012). The different physical parameters of soil, for instance, soil pH, are found to be largely interconnected to the presence as well as composition of microbial communities (Rousk et al. 2010) where addition of beneficial microbes to those which are already inhabiting the soil can upsurge the nutrient uptake by plants, upturn the plant growth, deliberate resistance to several kinds of abiotic stresses, and subdue disease (Chaparro et al. 2012). This living portion of soil is highly dynamic and potentially self-sustaining, which reduces the requirement for recurrent applications that thereby can circumvent the problematic infestation of pests as well as pathogens developing resistance to the dealings (Lucas 2011). The advantageous microbiota flourishing in this atmosphere have the capability of taking up the space as well as nutrients made accessible for probable pathogenic intruders on a very quick basis as compared to the pathogens (Kaymak 2011). This act of microbial "sealing off" of undefended ecological positions is coupled with the increase in the soil's capability of resisting pathogenic conquest, amplified produces, nutrient procurement, stress tolerance, and disease resistance to the plant host (Lugtenberg and Kamilova 2009). The huge microbial diversity sheltered in soil ecosystems also works as strong peacekeepers for recycling, impounding, and supplying of different nutrients to plants. The other beneficial attributes of soil microbiota encompass mineral chelation, pathogen suppression, improvement of soil aggregation, and bioremediation of the soils (Sahu et al. 2018) which constitutively improves soil health. Therefore, in order to attain strong and productive plants, the maintenance of soil quality is of utmost prominence. Besides, the soil microbiota can also be employed as the indicator of soil quality attributable to its compassion to slight changes in the soil environment subsequent to different ecological strains or natural unrests (Sharma et al. 2010). The elevations in the levels of species richness as well as diversity yield extraordinary purposeful redundancy within the soil microbiome, which further promotes its quicker recovery throughout the stress. The extraordinary functional redundancy in the diversity of soil microbiota also deliberates shield against numerous soilborne diseases (Yin et al. 2000; Nannipieri et al. 2003). The richness of microbial range results in a stable microbiome that does not permit the flourishment of pathogenic microbes. There are numerous key factors convoluted in the soil health. Freshly, the community consistency has also been acknowledged as an imperative factor in community functioning, soil health, and plant productivity. The evenness of microbial community also warrants that no individual microbial taxum is able to take over and flourish, upsetting the ecological balance (Elliot and Lynch 1994).

3.3 Microbes for Degradation of Toxic Xenobiotic Compounds

The completion of the twentieth century marked a significant and perpetual hike in the worldwide grain production with an increase of 700 million tons to 500 million tons now (FAO 2018). Out of the major food crops, a greater portion equaling to 80% of human ingestion is represented by the cereal crops. The production of food crops has to encounter a number of challenges, and one among them is the invasion of crops by several pests throughout the usual growth or storage of crops. For instance, China, although principally being an agriculturally dominating nation, loses 8.8% equivalent to 40 million tons of the total grain production as a result of insect pests annually (Pimentel et al. 2001). India, being a major producer of cereals, produces around 250 million tons of grain annually, but it also has to sacrifice 11–15% of the total production equaling 27.5–37.5 million per year, due to different pests and other reasons (Walter et al. 2016). The developments in organic chemistry have largely contributed to the synthesis and development of plentiful novel organic composites, mostly xenobiotics. A greater portion of such xenobiotic compounds is represented by pesticides, which largely found application in agricultural zones (Duong et al. 1997). Therefore, for the purpose of circumventing such damages, pesticides are extensively applied for checking agronomic and domestic pests. The explicit usage of pesticides prevented the significant loss of food, but it led to the widespread distribution of pesticides in the different environments along with the agronomic harvests. Therefore, such an application of pesticides is responsible for a prodigious possible threat to the environment as well as human health (Chen et al. 2007). Although these have contributed much toward the improvement of quality of the human life, their widespread use which is coupled with the generation of unavoidable concomitant waste has largely intensified the complication of releasing toxic wastes in the environment. Though much xenobiotic composites can degrade swiftly in the soil systems, some persist in the environment for an extended period of time and thereby are potentially menacing (Conant 2005). The extent of pesticide contamination is not limited up to the soil and harvests, but they also further intrude the groundwater systems in addition to the marine environment, thereby unswervingly intimidating human as well as environmental health. The presence of such xenobiotic compounds is supposed to affect the ecosystems in a number of ways, such as dwindled soil fertility, soil acidification, nitrate leaching, increased resistance in flora and fauna, groundwater as well as surface contamination, and adulteration of agrarian soils (Kumar et al. 2018). A vast array of limitations caused by these xenobiotic compounds as well as the increasing environmental concerns coupled with the promotion of sustainability in agroecosystems have led to banning of several classes of pesticides in preceding years. Therefore, with the intention of solving the ambiguity amid elevated yields and their ill effects, the quest for alternate approaches is largely under consideration. There can be several ways like pesticides having lower harmfulness and extraordinary competence which also yields a lower residual pesticide ought to be established and industrialized (Kumar et al. 2018) which seems to be a hellacious job. On the flip side, the biological methods targeting degradation of residual pesticidal particles seem to be worthy of getting consideration. Studies on microbial degradation of pesticide residues originated in the 1940s, and as people pay more attention to the environment, the research on the degradation process and degradation mechanism of organic pollutants has been deeply studied (Rangasamy et al. 2018).

Bacteria in the natural world are capable of degrading the residual pesticidal particles, which seems to be an economically viable as well as ecologically responsive alternate which would not cause any kind of secondary pollution. However, the competence of microbial systems is found to be moderately slow as the natural environment is found to be multifaceted and unpredictable, which largely distress the practicability as well as efficacy of microbial degradation of pesticidal particles. Subsequently, a vast array of scientific community has devoted much time on the studies of bacterial approach of pesticide degradation and had a clear consideration of the different detoxification mechanisms of various organic pesticides. A great figure of microbes possessing the ability of degradation as well as conversion of pesticides have been isolated (Kumar et al. 2018). Therefore, the existing studies of biodegradable pesticides are principally focused on the role of microorganism in the soil, such as bacteria, fungi, and actinomycetes (Singh 2008), where the principal roles are played by bacteria and fungi. The bacterial ability of inducing mutant strains, endowed with a variety of biochemical capability to adaptive environs, and therefore allowing enhanced in-depth study makes them superior agents for bioremediation of such contaminated environments. Although a vast array of bacterial communities possess the ability of degrading pesticides, the research is largely focused on only some members of the bacterial community. A great diversity of *Pseudomonas* species encompassing *Pseudomonas stutzeri*, *P. putida*, *P. nitroreducens*, *P. aeruginosa*, and *P. fluorescence*, retrieved from different agronomic farms and polluted discharges through different sections, has established to be much effective in the biodegradation of pesticides. Some strains of lactic acid bacteria, for instance, *Leuconostoc mesenteroides*, *Lactobacillus brevis*, *L. plantarum*, and *L. sakei*, are also acknowledged for their ability of utilizing pesticides as a solitary source of carbon and phosphorus (Cho et al. 2009).

Several fungal species such as *Aspergillus niger*, *A. fumigatus*, *Cladosporium cladosporioides*, *Penicillium raistrickii*, and *A. sydowii* have also been retrieved from numerous polluted situates and are also confirmed to possess the aptitude of degrading diverse pesticides. Likewise, different genera of algae, for instance, *Stichococcus, Scenedesmus*, and *Chlorella*, and some cyanobacteria like *Nostoc*, *Anabaena*, and *Oscillatoria* have been recognized to have the efficiency of transforming different pesticides (Kumar et al. 2018). Therefore, the increasing evidences of the microbial capability of transforming pesticides has directed the focus of different researchers across the globe toward the exploration of microbial diversity, predominantly at the polluted sites. However, the mere occurrence of microbes is not sufficient, but an appropriate environment coupled with diverse degradation attitudes, for instance, hydrolysis and adsorption, is also required. Besides, the enzymatic solicitations targeting pesticidal degradation are also attracting much attention, and the genetically modified microorganisms have also been deliberated to upsurge the potentialities of these microbes and augment the proportions of biodegradation (Tang et al. 2009). Several academics have emphasized the occurrence of *oph* gene in the microbial systems that vitiate organophosphorus pesticides and hydrolase as the principal enzyme behind the process. The approach of using enzymes as well as the associated genes governing the degradation processes can prominently augment the consideration of the biodegradation process and therefore can largely benefit the bioremediation efforts.

3.4 Microbes as Biofertilizers

Plants necessitate nutrients in adequate and secure quantity in order to nurture optimally (Chen et al. 2006). The major constriction which limits crop productivity in emerging countries particularly in resource-deprived nations, that too, on a global basis, is the soil infertility. The truncated fertility does not allow the agrarian communities to get more benefit from the amended crop cultivars and more fruitful agricultural performs. The green revolution marked the unambiguous usage of fertilizers of chemical origin for augmenting plant development and production efficiency along with the replenishment of soil nutrient eminence (Mohammadi and Sohrabi 2012). Although they have contributed a lot toward the development of superior agronomic practices for obtaining an elevated level of production, their continuous usage has also awarded several, for instance, increased prices, inaccessibility of plants toward a major proportion of nutrients, and lethal and nonbiodegradable attitude, which further affects the environmental systems and turns the soil resources incongruous for farming practices. Thus, the employment of fertilizers of biological origin seems to be a competent substitute for enhancing the productivity as well as upgrading the nutrient status of agroecosystems. The approach of using biofertilizers is primarily centered upon the fertilizer's biological origin especially the microbes, counting bacteria as well as fungi. Since these are resources of biological origin, therefore, they also behave as eco-friendly elements and thus maintain the healthy status of the environment. The principal intention of using biofertilizers is to upsurge the organic contents of agricultural systems which further upgrades the structure of soil along with a reduction in the forfeiture of essential nutrients like zinc, phosphorus, iron, nitrogen, iron, and calcium (Lal and Greenland 1979). Biofertilizers are also known as "microbial inoculants" and can be usually defined as a formulation encompassing living or dormant cells of proficient microbial strains endowed with the capability of nitrogen fixation, phosphate solubilization, or cellulolytic microbes as well and are often employed for seed application, soil, or composting zones with the prime aim of augmenting the population of these microbes, along with the acceleration of definite microbial practices for improving the degree of accessibility of nutrients in a definite form which is effortlessly obtainable by the plant systems (Giri et al. 2019). Biofertilizers function as a basis of all the nutrients owing to their capability of solubilizing multifaceted form of nutrients into soluble and easily accessible form (Singh et al. 2018). There are numerous factors which should be strictly taken into consideration before the formulation of any kind of biofertilizer, such as the growth sketch of microorganism, optimal conditions required for growth, and preparation of inoculum. Furthermore, the survival in carrier method along with its efficacy in the field conditions is inevitable for preparing any kind of biofertilizer.

The marketable biofertilizers are established by coating of numerous bacterial members such as *Rhizobium, Azotobacter, Bacillus, Azospirillum,* and *Pseudomonas* on the seeds, and this process is said to be bacterization. These microbes secrete several compounds which assist in making their formulations. For example, azotobacterin is secreted by *Azotobacter chroococcum*, and phosphobacterin is secreted by *Bacillus megaterium* (Kumar and Bohra 2006). It is not a mandatory process that the bacteria will surely make a symbiotic relationship for benefiting the plants, but it also boosts the development of lateral root hairs which further aids in an enhanced level of mineral and water uptake, also upsurges nitrogen accessibility, and discharges numerous plant growth hormones and other growth motivating factors which collectively direct the plant to increase its photosynthetic capability, thereby eventually improving nutrient eminence of the plants.

The microbes that are mainly exploited as components of biofertilizer are nitrogen fixers, potassium solubilizer and phosphorus solubilizer. Most of the bacteria included in biofertilizer have close relationship with plant roots. Rhizobium has symbiotic interaction with legume roots, and rhizobacteria inhabit on root surface or in rhizosphere soil. Nitrogen is considered to be a very vital element for all living systems, and its unavailability strongly retards the plant growth. The rhizobial biofertilizers have got the unique ability of fixing around 50–150 N/ha/annum. Therefore, the process of biological nitrogen fixation (BNF) is deliberated as an essential process for the maintenance of nitrogen stability in soil environments. Thus, BNF is considered to be a unique way of transforming the elemental and unavailable nitrogen into a form that is easily accessible to plant (Gothwal et al. 2007). This approach is being utilized continuously by employing biofertilizers in the legumes and other crops to uplift their yield as well as quality (Kannaiyan 2002). The biofertilizers for nitrogen fixation are alive microbial inoculants capable of fixing atmospheric nitrogen either in a symbiotic way, for instance, *Rhizobia*, *Frankia*, and *Azolla*, or in an associative or free-living forms like *Azospirillum* and *Azotobacter* (Gupta 2004). There is a vast array of nitrogen-fixing microbes allied with nonleguminous plants which comprises species of *Achromobacter, Rhodopseudomonas, Alcaligenes, Rhodospirillum, Methylosinus, Arthrobacter, Xanthobacter, Klebsiella, Mycobacterium, Acetobacter, Corynebacterium, Azomonas, Herbaspirillum, Beijerinckia, Bacillus, Clostridium, Desulfovibrio, Enterobacter, Lignobacter, Erwinia, Derxia, Campylobacter*, and *Mycobacterium* (Wani 1990). Although a great number of microbes have been retrieved from the rhizospheric portion of cereal crops, the members of *Azotobacter* and *Azospirillum* are largely employed under field conditions.

The other group of microbes which are most often used are phosphate-solubilizing microorganisms. The application of such microbes especially bacteria and fungi makes available the insoluble forms of phosphorus to the plant systems (Gupta 2004). A number of bacteria existing in soil along with the population of some fungi solubilize the phosphate by secretion of organic acids (Gupta 2004). The secretion of such acids brings down the level of soil pH and thereby leads to the solubilization of the complex phosphatic forms. Therefore, these phosphate-solubilizing bacteria (PSB) are greatly acknowledged for transforming the inorganic and unavailable phosphorus to the soluble forms, i.e., HPO_4^{2-} and $H_2PO_4^-$. This solubilization process is mediated through a myriad of mechanisms which include organic acid secretion, chelation, and ion exchange reactions as well. Consequently, the employment of PSB in agricultural systems can be used to combat the increasing manufacturing costs of phosphate fertilizers and would surely contribute in mobilization of the insoluble fertilizers to the plant bodies (Chang and Yang 2009; Banerjee et al. 2010). The most promising soil bacterial groups are represented by the ecto-rhizospheric species of *Bacillus* as well as *Pseudomonas* along with some endosymbiotic rhizobia for operative phosphate solubilization (Igual et al. 2001). Different microbes which display effective solubilization of phosphate are represented by *Pseudomonas*, *Rhizobium*, *Bacillus*, and *Enterobacter* accompanied by some fungal members such as *Penicillium* and *Aspergillus* (Whitelaw 2000). *Bacillus megaterium, B. polymyxa, B. subtilis, B. circulans, B. sircalmous*, *Pseudomonas striata*, and *Enterobacter* are among the most potent strains of phosphate solubilizers (Subbarao 1988). Several species of *Bacillus*, for instance, *Bacillus mucilaginous*, have the capability of potassium solubilization also. Therefore, biofertilizers play an indispensable role in upsurging the productivity of food crops by the possession of numerous beneficial attributes and thus owe the immense capability of either replacing the synthetic fertilizers in part or a total replacement that can be carried out by the means of several targeted approaches.

3.5 Microbes as Biocontrol Agents

It is a tenacious matter that the global farming community has to experience a great economic loss due to the massive quantity of plant pathogens which varies from the minutest viroid comprising merely of a single-stranded RNA to further multifarious pathogens, for instance, viruses, bacteria, fungi, oomycetes, and nematodes, which are responsible for numerous significant plant diseases and thereby are also accountable for chief harvest damages. Even though there is a greater number of other factors also which are also held responsible for reduction in crop production, the damage caused by pests and pathogens plays an influential role in the harms on a global basis (Roberts et al. 2006). The plant ailments are responsible for an appraised loss of 40 billion dollars globally on an annual basis, either in a direct manner or in an indirect way. The pathogenic infection are liable for around 20–40% of fatalities in the crop yields (Savary et al. 2012). The magnitudes of the plant diseases vary from foremost destructions to the slight pains. Several plant diseases are found to be exceedingly damaging and disastrous on a great scale. For instance, the potato late blight caused by the fungi *Phytophthora infestans* resulted in food scarcities which led to a million deaths and relocation of around 1.5 million people from Ireland in the year 1840 (Donnelly 2002). The yearly harms of potato, the fourth largest food crop, as a result of late blight are conservatively assessed to be around US$6.7 billion per year. The other major notable example is of the disease brown leaf spot of rice which is instigated by *Helminthosporium oryzae* and is found to be prevailing largely in Asia, Africa, South America, and the USA. It was also a major rice fungal disease of historic attention (Padmanabhan 1973). It was responsible for causing austere destruction by plummeting rice harvests which resulted in the death of around two million people in Bengal as an outcome of the catastrophic scarcity in the year 1940s (Tatum 1971; Ullstrup 1972). The thing of utmost concern for mankind is the unparalleled current tendency of new fungus and fungus-resembling pathogenic signals that have amplified by over and above seven times since 2000 (Evers et al. 2007). The continued agricultural practices of precise monocultures improved global trade, and the practice of growing only some restricted cultivars is largely responsible for this increase in the population of pathogenic microbes.

These acts also endorse the development and progression of pathogenic strains with increased virulence, repeatedly with accumulative tolerance toward pesticides which not only distress the agricultural productivity but also affect several native wild species (Ab Rahman et al. 2018). Therefore, the mounting global population necessitates an effectual management as well as resistor for plant diseases in food crop production. Crop defense always plays an imperative part in shielding crop output contrary to competition from pathogens (Oerke and Dehne 2004). The modern agronomic practices now necessitate a robust impulse for mounting low-input and further sustainable agrarian practices that comprise substitutes to the chemicals employed for monitoring pests and diseases, which act as a chief and dynamic element responsible for substantial fatalities in agricultural production. The ever-increasing adverse effects of chemicals used for pest control on human health, the ecosystem, and the living creatures have directed the researchers' focus on potent biological control microorganisms as doable substitutes for managing pests and plant pathogens (Ab Rahman et al. 2018). There are ever-increasing confirmations that validate the capability of leaf as well as root-allied microbes to intensify the plant efficacy as well as yield in the cropping systems. It is much imperative to comprehend and appreciate the part of such microbes in stimulating growth and monitoring plant diseases as well; however, their presentation as biopesticides in the field conditions is still unpredictable (De Silva et al. 2019).

The employment of beneficial biocontrol microorganisms can be a viable option that could display potential of competing with the pathogenic microorganisms or can provide benefits by directly antagonizing pathogens by secreting antimicrobial composites (Mansfield 2000). The indigenous infection by pathogenic microbes can lead to the induction of systemic acquired resistance, but the capability of nonpathogenic rhizobacteria to prime plants for induced systemic resistance alongside different pathogens is much crucial and therefore is of substantial interest (Choudhary et al. 2007). This priming offers a better preparedness to plants that are able to respond faster and stronger to pathogen attack. The method of biologically controlling plant disease seems to be the preeminent choice for the manufacture of economically viable, environmental-friendly, and sustainability-promoting approach for shielding plants and other crops. Therefore, the biocontrol microorganisms are now widely being acknowledged as important tools for controlling plant diseases for an enhanced crop production in the sustainable agriculture (Azcón-Aguilar and Barea 1997). There is a great diversity of microbes which can be utilized as potent biocontrol agents. Nevertheless, a sound exploration of the multifaceted interactions amid plants, the environment, and the pathogens is quite indispensable for further consideration as the results may vary if the plants are already under an extensive load of disease (Mirzaee et al. 2015). The principal knowledge of piloting several research projects on the biocontrol was primarily meant for reduction in the dependence on the usage of agrochemicals due to several detrimental effects they lay on human health as well as on the environment. It was mainly accelerated around three decades due to increasing interest in the employment of useful microbes for suppressing of plant diseases, comprising the infections by plant parasitic nematodes as well (Cook and Baker 1983). The resultant biocontrol activity is often produced as a result of compound dealings, for instance, clampdown of the pest by use of other organisms or the use of antagonistic microbes to combat diseases and the introduction of host-specific pathogens. The employment of natural yields and chemical extracts of ordinary or modified microbes or gene products is another example of biological control. There is a vast array of interactions among the microbial populations such as mutualism, protocooperation, commensalism, neutralism, competition, amensalism, parasitism, and predation. All these biological control interactions amid plants and microorganisms happen unsurprisingly at a macroscopic as well as microscopic level (Gardener and Fravel 2002; Pal and Gardener 2006). The microbes inhabiting the rhizospheric portion of plants are deliberated to be superior biocontrol agents as the rhizospheric soil is considered to be microbiologically oppressive to numerous pathogens, attributable to the capability of this portion acting as a line of frontline defense against innumerable pathogenic occurrences. The occupation of roots by diverse beneficial microorganisms distributes their pathogen-alienating metabolic products into the root atmosphere where they result in direct or indirect suppression of pathogens (Shoda 2000). There is also the involvement of the phenomenon of antibiosis that happens as an outcome of the emission of diffusible volatile organic compounds, antibiotics, and toxins, along with the formation of extracellular cell wall-humiliating enzymes, for instance, pectin methylesterase, β-1,3-glucanase, chitinase, and β-xylosidase (Shoda 2000; Compant et al. 2005). The root systems of plants also deliberate a biological environment for progression of soil microbes that flourish on different root exudates as well as lysates which are utilized by the microbes as nutrients. The diversity of endophytic as well as free-living rhizobacteria harbored by the plants in their rhizospheric area utilize the nutrients secreted by the plant systems via their roots, and therefore grow and proliferate to secrete various metabolites in the soil systems which are found to control various plant diseases triggered by fungal or bacterial activities (Gray and Smith 2005; Kiely et al. 2006). In addition to it, the inhabitation of rhizospheric slot by different plant growth-promoting bacteria is further supported by the secretion of various kinds of allelochemicals, for instance, antibiotics, iron-chelating siderophores, biocidal volatiles, lytic enzymes, and detoxification enzymes (Glick 1995; Sturz and Christie 2003). Allelochemicals are also examples of secondary metabolites that are produced either in a direct way or in an indirect manner by plants and released into the root region as an outcome of various chemical and biochemical reactions (Tang et al. 1989; Shaw et al. 2006); however, they can also be released by the allied fungal and bacterial inhabitants. Several bacterial agents such as the nonpathogenic *Pseudomonas* and rhizobacteria are endowed with the potential of inducing systemic resistance in plants which honors the plant with the ability of protecting itself against a great deal of pathogenic viruses, bacteria, and fungi (Pieterse et al. 2014). Therefore, it seems that plants might have evolved their own language that makes them capable of interacting with their allied microbiota by secreting a greater diversity of chemical compounds via their leaves as well as roots. This phenomenon aids the plant systems to attract and select precise microbial population in the rhizospheric as well as phyllospheric environments that can offer explicit assistances that are desirable for the plant systems (Vorholt 2012).

3.6 Biofortification of Crops Using Microbes

The monster of undernourishment is deliberated among the supreme exalted universal challenges to mankind. It bothers almost a billion or more of the global people in both advanced and emerging nations. The disgrace of malnutrition takes account of food-associated prolonged diseases in addition to the explicit nutrient paucities which further are held responsible for morbidity as well as abridged physical and psychological development. The occurrence of micronutrient paucity in human beings is largely reported, and the members of emerging nations mainly rely on the food from the staple crops which are further described by abridged bio-obtainability of vital micronutrients. The pervasiveness of such micronutrient paucities further intensifies the menace of widespread encumbrance of illness in different low- as well as middle-income nations (Black 2014), and the members of poor families are not able to manage expensive foods enriched with nutrients. As per the reports of United Nations System Standing Committee on Nutrition, the micronutrient hunger is deeply allied with over and above 50% of the total child mortality, and it further exhibits the leading risk factors for maternal death cases. Iron (Fe), zinc (Zn), and selenium (Se) are deliberated to be the micronutrients of utmost importance, and their intake is apposite for sustaining numerous life processes (UNSSCN 2004). The scarcity of any of the micronutrients has various deleterious effects on human health which are conveyed via numerous diseases. Zinc is an indispensable micronutrient for almost all the living entities comprising human beings, and its structural role in different proteins also makes it a significant micronutrient. Its deficiency is at utmost prevalence which results in abundant health-associated concerns, for instance, growth weakening, increased vulnerability toward different infections, diarrhea, retarded growth, delayed recovery of wounds, skeletal aberrations, and amplified danger of abortion (Salgueiro et al. 2000). On the other hand, the paucity of iron provokes nutritional anemia and also results in damaged working of immune system among the children along with the diminished neurocognitive growth (Murray-Kolb 2013). Selenium has numerous indispensable roles to play in a vast array of metabolic paths. Its deficiency is largely responsible for several heart diseases, reduced male fertility, hypothyroidism, weakened immune system, and high risk of infections, cancer, oxidative stress-related conditions, and epilepsy (Hatfield et al. 2014). The deficiency of different micronutrients also results in a weakened DNA molecule prone to easy damage. Therefore, there are ever-increasing endeavors targeting an enhanced assimilation of different micronutrients in plant systems.

Conversely, numerous approaches to augment the mineral elements uptake as well as food fortification haven’t been fruitful every time. The approach of biofortification is only allied with entrusting the nutrient accumulation in the plant cells which makes it different from the “standard fortification” which encompasses practice of additives with the foods (Khan et al. 2019). The microbes having benefit effects on plant growth promotion are acknowledged for fortification of micro- as well as macronutrient concentrations in the essential food crops. There is a large number of mechanisms responsible for the fortification process, for instance, phosphate solubilization, zinc solubilization, siderophores production, and nitrogen fixation. The introduction of potent microbes in consort with the mineral fertilizers have the capability of enhancing the mineral uptake in turn growth as well as yield. Consequently, the biofortification of different food crops as an outcome of plant growth-promoting microbiota has been encouraged as a unique stratagem not only for upsurging the level of micronutrients in eatable food crops but also to elevate the output on soils having lesser fertility (Khan et al. 2019). Microbes are unseen soil engineers that are responsible for maintaining the status of a healthy soil and for the construction of a center for diverse biogeochemical cycles (Gadd 2010). A large number of microbes inhabiting soil ecosystems, for instance, bacteria, cyanobacteria, actinomycetes, and mycorrhiza, provide an environmental pleasant attitude for upgraded nutrient uptake along with the enhancement in plant growth. Microbes, more precisely the plant growth-promoting rhizobacteria (PGPR), are settled in the portion of rhizosphere and are capable of competently colonizing the plant roots, and they award the plants with many unique and beneficial attributes (Prasad et al. 2015). These microbes adopt diverse mechanisms for playing their central part in upsurging the nutrient consumption efficacy of the plants. These microbes are uniquely capable of playing an imperative role in the mineralization of organic matter coupled with the biotransformation of several inorganic nutrients which imparts these microbes with the innovative ability of biofortification. There are several other characteristics of these microbes, for instance, solubilization, chelation, and oxidation/reduction which have the aptitude of directly influencing nutrient accessibility (Khan 2005; Bonfante and Genre 2015). Besides obtaining improved crop yields, the present-day agricultural systems are mainly centered for producing nutritious safe food crops endowed with enriched micronutrient level especially in the edible part of the plant. Since the human population is predominantly reliant on diets grounded on staple food crops, therefore, consumption of foods with deprived or reduced concentration of micronutrients is greatly responsible for severe health concerns in human beings. The paucity of these micronutrients (selenium, zinc, iron, manganese, copper, and vitamins) in plant systems as well as in human beings is described as “hidden hunger” (Sharma et al. 2016) and imparts the risk of malnutrition among the global mankind. Consequently, the execution of the attitude of biofortification seems to be an imperative as well as lucrative method for endowment of distinguished and dominant solution for the production of crops having higher concentrations of required micronutrients. The plant growth-endorsing microbes are reportedly known for the biofortification of micronutrient components in different food harvests above and beyond the improvement in the soil productiveness as well as in the crop yield (Rana et al. 2012).

Iron, an important micronutrient, is present in the oxidized states owing to the prevalence of oxygen-rich environments. Different bacterial as well as fungal inhabitants of the soil ecosystems have evolved various unique mechanism for iron sequestration, for instance, the production of some lower-molecular-mass compounds called as siderophores which are immensely compassionate concerning Fe^{3+} ions. These siderophores are eventually up taken by the plant systems via roots for conveyance of the sequestered iron to the plants. Hence, the siderophores of microbial origin are enormously capable of augmenting plant growth as a result of improved uptake of iron accompanied with inhibition of the pathogenic microbes by dint of competitive advantages (Srivastava et al. 2013). A diverse array of bacterial soil inhabitants have been largely acknowledged for the siderophore fabrication, viz., *Rhodospirillum, Bacillus, Azospirillum, Burkholderia, Pseudomonas, Azotobacter, Serratia, Arthrobacter, Enterobacter,* and *Rhizobium*, along with different fungal partners like *Syncephalastrum*, *Aspergillus*, *Rhizopus*, and *Penicillium* (Khan et al. 2019). There are numerous kinds of siderophores which are often secreted by the plant-allied microbiota, for instance, catecholate, carboxylate, and hydroxymate, and their exudation diverges across different species. Additionally, the siderophore production of mixed type has also been reported by many microbial species (Wandersman and Delepelaire 2004). Thus, the iron biofortification in different food crops is greatly supported by the secretion of these siderophore molecules. The microbes allied with plant systems also implement a number of tools for zinc solubilization, for instance, chelation (Whiting et al. 2001), dropping down the pH of soil (Subramanian et al. 2009), and by means of enhancing the root progression as well as the effective absorption area of the root (Bürkert and Robson 1994). The chelation of metallic ion zinc by diverse microorganisms coupled with enhancement in its availability for plant systems is a well-acknowledged occurrence. The microbial production of zinc-chelating compounds, metallophores, which sequester the zinc, is later released at the root surfaces and thus becomes available for the plants for its biofortification in the plant parts (Saravanan et al. 2004). Diverse microbial allies of plants, such as *Enterobacter, Pseudomonas, Bacillus, Microbacterium*, and different arbuscular mycorrhizae, are unbelievably proficient for zinc solubilization from composite mixtures which subsequently improves quality as well as nutrient content of the plants and their produces. Therefore, it can be said that the microbial approach of increasing nutrient content which further improves the quality of food crops is an economically viable and sustainability-advocating practice of superior crop production.

3.7 Enhancement of Abiotic Stress Tolerance Ability of Plants

The most discouraging phenomenon in the production of food crops is the appearance of several kinds of abiotic stresses which appear as an outcome of the intrinsic edaphic aspects as well as due to the anthropogenic activities. These stresses may be persuaded by the soil salinity, heavy metal pollution, and the prevalence of different organic pollutants. The developing nations has to face the problems of such abiotic stresses in a major proportion of their agricultural land which expressively condense the production of different crops (Lal 2000). The different abiotic stresses allied with the edaphic elements are comprised by soil-associated constrictions, such as reduced fertility, elevated salt content, low pH, and the occurrence of toxic heavy metals in the plant rhizosphere. In addition to these chemical factors, numerous physical restraints of the soil like poor texture, compaction, rockiness (Lal 1987), and slope abruptness (Lal 1998) also strongly affect the crop production. All these factors are held responsible for determination of the water-holding capability of soil, the cation-exchange capability, and the level of root communication with the soil and thus strongly effect the plant nutrient acquirement and crop harvests (Marchner 1995). The other abiotic stresses appear as a result of increased anthropogenic activities, such as superfluous irrigation patterns, and using saline water for irrigation purposes has backed the salt content in the agricultural soils. The employment of sewage water for irrigating fields and using sewage sludge as fertilizer have led to the accretion of poisonous heavy metals in various areas of the global agricultural sector. Another omnipresent difficulty arises as a result of the haphazard usage of organic pollutants and chemicals which persist in the soil environment for a longer duration of time and potentially interrupt the symmetry of the soft soil (Selvakumar et al. 2012). With the continuously deteriorating qualitative as well as quantitative aspects of freshwater assets, and underprivileged irrigation groundwork, the drought management especially in emerging nations seems to be imperfect. The insufficiency of moisture contents in agricultural soils is not just having a direct effect on the crop yields, but it also decreases the yields by influencing the obtainability as well as the nutrient conveyance. The drought stress also affects the crop yields by altering the hormonal balance of the plant systems as it is responsible for a reduction in the levels of cytokinin as well as a hike in the abscisic acid content in the leaves, which further leads to closing of stomatal pores (Figueiredo et al. 2008). Since water acts as a medium for carrying the nutrients from the plant roots, therefore, the low moisture level is responsible for a decreased diffusion of nutrients over small distances and the mass flow of water-soluble nutrients such as nitrate, sulfate, Ca, Mg, and Si over longer distances (Barber 1995). The drought is also responsible for a reduction in the obtainability of carbon dioxide for photosynthesis that further promotes the construction of reactive oxygen species that are highly potent for damaging the DNA and may also affect the functioning of the cell membranes (Sgherri et al. 2000). The salinity stress also affects the productivity of agroecosystems as it does not allow the plants to extract water from the soil. Additionally, some salts penetrate the plant systems and disturb various physiological processes of the plants which may lead to plant death (Tester and Davenport 2003).

Microbes that assist plants in alleviating certain kinds of abiotic stresses are awarded with several specified purposeful attributes. The plant systems are known for accretion of ethylene hormone under the conditions of stress (Jackson 1997). The microbial production of the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase is responsible for the cleavage of the ACC which acts as the precursor particle of ethylene, and the production of this enzyme significantly reduces the concentration of this gaseous hormone in the plants under stress (Abeles 1973). Some PGPR strains are endowed with the capability of removing stress by the possession of certain attributes. One such is the induced systemic tolerance (IST) which is meant to house the physical as well as chemical variations induced in the plant systems as a result of microbial activities which further aids plant systems in tolerating various abiotic stresses (Yang et al. 2009). The inoculation of the plants with the

PGPR *Paenibacillus polymyxa* is reported to have an improved tolerance of the drought stress (Timmusk and Wagner 1999). Plant systems suffer a lot due to the oxidative damages under abiotic stress conditions. The production of various antioxidant enzymes by numerous rhizobacterial species helps the plants in tolerating drought stress (Bowler et al. 1992; Scandalios 1994). The drought stress also leads to variations in the soil structures which disturbs the agronomic processes and affects the crop yields in a considerable way. In this case, the microbes which are known for the secretion of exopolysaccharide (EPS) seem to be of utmost importance. The EPS fashioned by such microbes defends these microorganisms from the hostile environmental conditions and thus permits their existence. The EPS also endows these microbes with a unique property of desiccation tolerance (Hartel and Alexander 1986; Konnova et al. 2001). The EPS secretion also allows the microbes to attach and inhabit the roots in an irreversible manner owing to engrossment of a system of fibrillary material which aids in the formation of a permanent connection amid bacteria and the root surface (Sandhya et al. 2009). The plant systems receiving treatments of EPS-constructing microbes exhibit an improved confrontation to the water stress (Bensalim et al. 1998). The EPS matrix is supposed to offer a micro-environment which clutches water and retains it for a longer interval of time as compared to the surrounding atmosphere and thus confers the bacteria as well as the protection of plant roots against desiccation (Hepper 1975). The EPS fabrication is also known to enhance the permeability by augmenting the soil aggregation along with the maintenance of developed water potential nearby the roots, thus allowing an increased uptake of nutrients by the plant systems, which further results in improved plant growth apart from the defense against drought stress (Alami et al. 2000).

3.8 Conclusion and Future Prospects

The products of microbial origin have the capability of enhancing crop yields and are equally potent to bring out the replacement of agrochemicals as well as chemical fertilizers. They can also improve the quality of the soil polluted by the explicit usage of chemicals for enhancing productivity of agricultural systems. Microbes are auspicious tools and can also augment the qualitative aspects of food crops and thus can be of immense importance for upgrading global health status of human beings. This potential of microbes is being utilized by several industries in which products of microbial origin are being formulated as biocontrol agents and effective biofertilizer products. The lab work is often carried out to unveil unique possessions of the microbial world, but at various times, the deeds of microbial technologies often fail to prove themselves at the field conditions. The belongings of microbial merchandises are often found to be unpredictable and unreliable between diverse studies and are found to be inconsistent under variable atmospheric conditions. Several times the microbial population fails to compete with the autochthonous microbiota which is a major logjam in the large-scale implementation of the technology.

Consequently, there is a burning requirement for the improvement of selection methods and implementation practices. Apart from this, a better understanding of the communications amid inoculated microbial strains and innate microbiota is strongly required under field conditions.

References

Ab Rahman SF, Singh E, Pieterse CM, Schenk PM (2018) Emerging microbial biocontrol strategies for plant pathogens. Plant Sci 267:102–111

Abeles FB (1973) Ethylene in plant biology. Academic, New York

Ahmad Z, Imran M, Qadeer S, Hussain S, Kausar R, Dawson L, Khalid A (2018) Biosurfactants for sustainable soil management. Adv Agron:81–130. https://doi.org/10.1016/bs.agron.2018.02.002

Alami Y, Achouak W, Marol C, Heulin T (2000) Rhizosphere soil aggregation and plant growth promotion of sunflowers by exopolysaccharide producing Rhizobium sp. strain isolated from sunflower roots. Appl Environ Microbiol 66:3393–3398

Azcón-Aguilar C, Barea JM (1997) Arbuscular mycorrhizas and biological control of soil-borne plant pathogens–an overview of the mechanisms involved. Mycorrhiza 6(6):457–464

Banerjee S, Palit R, Sengupta C, Standing D (2010) Stress induced phosphate solubilization by 'Arthrobacter' Sp. and 'Bacillus' sp. isolated from tomato rhizosphere. Aust J Crop Sci 4(6):378

Barber SA (1995) Soil nutrient bioavailability: a mechanistic approach, 2nd edn. Wiley, New York

Bell CW, Asao S, Calderon F, Wolk B, Wallenstein MD (2015) Plant nitrogen uptake drives rhizosphere bacterial community assembly during plant growth. Soil Biol Biochem 85:170–182

Bensalim S, Nowak J, Asiedu SK (1998) A plant growth promoting rhizobacterium and temperature effects on performance of 18 clones of potato. Am J Potato Res 75:145–152

Berendsen RL, Pieterse CM, Bakker PA (2012) The rhizosphere microbiome and plant health. Trends Plant Sci 17(8):478–486

Bilali HE, Allahyari MS (2018) Transition towards sustainability in agriculture and food systems: role of information and communication technologies. Inf Process Agric 5:456–464. https://doi.org/10.1016/j.inpa.2018.06.006

Black RE (2014) Global distribution and disease burden related to micronutrient deficiencies. In: International nutrition: achieving millennium goals and beyond, vol 78. Karger Publishers, pp 21–28

Bonfante P, Genre A (2015) Arbuscular mycorrhizal dialogues: do you speak 'plantish' or 'fungish'? Trends Plant Sci 20(3):150–154

Bowler C, van Montagu M, Inze D (1992) Superoxide dismutase and stress tolerance. Annu Rev Plant Physiol Plant Mol Biol 43:83–116

Brunori G, Barjolle D, Dockes A-C, Helmle S, Ingram J, Klerkx L, Moschitz H, Nemes G, Tisenkopfs T (2013) CAP reform and innovation: the role of learning and innovation networks. EuroChoices 12:27–33. https://doi.org/10.1111/1746-692x.12025

Bürkert B, Robson A (1994) Zn uptake in subterranean clover (Trifolium subterraneum L.) by three vesicular-arbuscular mycorrhizal fungi in a root-free sandy soil. Soil Biol Biochem 26(9):1117–1124

Chang CH, Yang SS (2009) Thermo-tolerant phosphate-solubilizing microbes for multi-functional biofertilizer preparation. Bioresour Technol 100(4):1648–1658

Chaparro JM, Sheflin AM, Manter DK, Vivanco JM (2012) Manipulating the soil microbiome to increase soil health and plant fertility. Biol Fertil Soils 48(5):489–499

Chen YP, Rekha PD, Arun AB, Shen FT, Lai WA, Young CC (2006) Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. Appl Soil Ecol 34(1):33–41

Chen S, Sun D, Chung JS (2007) Treatment of pesticide wastewater by moving-bed biofilm reactor combined with Fenton-coagulation pretreatment. J Hazard Mater 144(1–2):577–584

Cho KM, Math RK, Islam SMA, Lim WJ, Hong SY, Kim JM, Yun MG, Cho JJ, Yun HD (2009) Biodegradation of chlorpyrifos by lactic acid bacteria during kimchi fermentation. J Agric Food Chem 57:1882–1889

Choudhary DK, Prakash A, Johri BN (2007) Induced systemic resistance (ISR) in plants: mechanism of action. Indian J Microbiol 47(4):289–297

Compant S, Duffy B, Nowak J, Clément C, Barka EA (2005) Use of plant growth-promoting bacteria for biocontrol of plant diseases: principles, mechanisms of action, and future prospects. Appl Environ Microbiol 71(9):4951–4959

Conant J (2005) Pesticides are poison, a community guide to environmental health. Hesperian Foundation, CA, USA

Cook RJ, Baker KF (1983) The nature and practice of biological control of plant pathogens. American Phytopathological Society

De Silva NI, Brooks S, Lumyong S, Hyde KD (2019) Use of endophytes as biocontrol agents. Fungal Biol Rev 33:133–148

DeFries RS, Ellis EC, Chapin FS III, Matson PA, Turner BL II, Agrawal A, Crutzen PJ, Field C, Gleick P, Kareiva PM, Lambin E (2012) Planetary opportunities: a social contract for global change science to contribute to a sustainable future. Bioscience 62:603–606

Donnelly JS (2002) Great Irish Potato Famine. The History Press

Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. Appl Soil Ecol 15(1):3–11

Duong MH, Penrod SL, Grant SB (1997) Kinetics of p-nitrophenol degradation by Pseudomonas sp.: an experiment illustrating bioremediation. J Chem Educ 74(12):1451

Elliot LF, Lynch JM (1994) Biodiversity and soil resilience. In: Greenland DJ, Szabolos I (eds) Soil resilience and sustainable land use, vol 31. CAB International, Wallingford, pp 353–364

Evers D, Bonnechère S, Hoffmann L, Hausman JF (2007) Physiological aspects of abiotic stress response in potato. Belg J Bot 1:141–150

FAO (Food and Agriculture Organization of the United Nations) (2018) Available online: http://www.fao.org/faostat/en/#data/QC

FAO (Food and Agriculture Organization of the United Nations), IFAD (International Fund for Agricultural Development), UNICEF, WFP (World Food Programme), and WHO (World Health Organization) (2017) The State of Food Security and Nutrition in the World 2017: building resilience for peace and food security. FAO, Rome

Figueiredo MVB, Burity HA, Martinez CR, Chanway CP (2008) Alleviation of drought stress in common bean (Phaseolus vulgaris L.) by co-inoculation of Paenibacillus polymyxa and Rhizobium tropici. Appl Soil Ecol 40:182–188

Frey SD, Knorr M, Parrent JL, Simpson RT (2004) Chronic nitrogen enrichment affects the structure and function of the soil microbial community in temperate hardwood and pine forests. For Ecol Manage 196:159–171

Gadd GM (2010) Metals, minerals and microbes: geo-microbiology and bioremediation. Microbiology 156:609–643

Gardener BB, Fravel DR (2002) Biological control of plant pathogens: research, commercialization, and application in the USA. Plant Health Progress 3(1):17

Gertsson UE, Alsanius BW (2001) Plant response of hydroponically grown tomato to bacterization. In: International symposium on growing media and hydroponics, vol 644, pp 583–588

Giri B, Prasad R, Wu Q-S, Varma A (2019) Biofertilizers for sustainable agriculture and environment. Springer International Publishing, Cham. ISBN 978-3-030-18932-7. https://www.springer.com/gp/book/9783030189327

Glick BR (1995) The enhancement of plant growth by free-living bacteria. Can J Microbiol 41(2):109–117

Goshu D, Kassa B, Ketema M (2013) Measuring diet quantity and quality dimensions of food security in rural Ethiopia. J Dev Agric Econ 5:174–185

Gothwal RK, Nigam VK, Mohan MK, Sasmal D, Ghosh P (2007) Screening of nitrogen fixers from rhizospheric bacterial isolates associated with important desert plants. Appl Ecol Environ Res 6(2):101–109

Gray E, Smith D (2005) Intracellular and extracellular PGPR: commonalities and distinctions in the plant-bacterium signaling processes. Soil Biol Biochem 37:395–412

Gupta AK (2004) The complete technology book on biofertilizers and organic farming. National Institute of Industrial Research Press, India

Hartel PG, Alexander M (1986) Role of extracellular polysaccharide production and clays in the desiccation tolerance of cowpea Bradyrhizobia. Soil Sci Soc Am J 50:1193–1198

Hatfield DL, Tsuji PA, Carlson BA, Gladyshev VN (2014) Selenium and selenocysteine: roles in cancer, health, and development. Trends Biochem Sci 39(3):112–120

Heckman DS, Geiser DM, Eidell BR, Stauffer RL, Kardos NL, Hedges SB (2001) Molecular evidence for the early colonization of land by fungi and plants. Science 293(5532):1129–1133

Hepper CM (1975) Extracellular polysaccharides of soil bacteria. In: Walker N (ed) Soil microbiology, a critical review. Wiley, New York, pp 93–111

Igual J, Valverde A, Cervantes E, Velázquez E (2001) Phosphate-solubilizing bacteria as inoculants for agriculture: use of updated molecular techniques in their study

International Food Policy Research Institute (2018) 2018 Global Food Policy Report. International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/9780896292970

Jackson MB (1997) Hormones from roots as signal for the shoots of stressed plants. Trends Plant Sci 2:22–28

Kannaiyan S (ed) (2002) Biotechnology of biofertilizers. Alpha Science Int'l Ltd

Kaymak HC (2011) Plant growth and health promoting bacteria. In: Maheshwari DK (ed) Microbiology monographs, vol 18. Springer-Verlag, Berlin, pp 45–79. https://doi.org/10.1007/978-3-642-13612-2_3

Kazan K, Lyons R (2015) The link between flowering time and stress tolerance. J Exp Bot 67(1):47–60

Khan AG (2005) Role of soil microbes in the rhizospheres of plants growing on trace metal contaminated soils in phytoremediation. J Trace Elem Med Biol 18(4):355–364

Khan MS, Zaidi A, Musarrat J (eds) (2009) Microbial strategies for crop improvement. Springer, Berlin

Khan A, Singh J, Upadhayay VK, Singh AV, Shah S (2019) Microbial biofortification: a green technology through plant growth promoting microorganisms. In: Sustainable Green Technologies for Environmental Management. Springer, Singapore, pp 255–269. https://doi.org/10.1007/978-981-13-2772-8_13

Kiely PD, Haynes JM, Higgins CH, Franks A, Mark GL, Morrissey JP, O'gara F (2006) Exploiting new systems-based strategies to elucidate plant-bacterial interactions in the rhizosphere. Microb Ecol 51(3):257–266

Konnova SA, Brykova OS, Sachkova OA, Egorenkova IV, Ignatov VV (2001) Protective role of the polysaccharide containing capsular components of Azospirillum brasilense. Microbiology 70:436–440

Kumar A, Bohra B (2006) Green technology in relation to sustainable agriculture. In: Green technologies for sustainable agriculture. Daya Publishing House, Delhi

Kumar S, Kaushik G, Dar MA, Nimesh S, Lopez-Chuken UJ, Villarreal-Chiu JF (2018) Microbial degradation of organophosphate pesticides: a review. Pedosphere 28(2):190–208

Lal R (1987) Managing the soils of sub-Saharan Africa. Science 236:1069–1076

Lal R (1993) Tillage effects on soil degradation, soil resilience, soil quality and sustainability. Soil Tillage Res 27:1–7

Lal R (1997) Degradation and resilience of soils. Philos Trans R Soc Lond (B) 352:997–1010

Lal R (1998) Soil erosion impact on agronomic productivity and environment quality. Crit Rev Plant Sci 17:319–464

Lal R (2000) Soil management in the developing countries. Soil Sci 165:57–72

Lal R (2009) Soil degradation as a reason for inadequate human nutrition. Food Sec 1(1):45–57

Lal R, Greenland DJ (1979) Soil physical properties and crop production in the tropics. Wiley

Liu S, da Cunha AP, Rezende RM, Cialic R, Wei Z, Bry L, Comstock LE, Gandhi R, Weiner HL (2016) The host shapes the gut microbiota via fecal microRNA. Cell Host Microbe 19(1):32–43

Lucas JA (2011) Advances in plant disease and pest management. J Agric Sci 149:91–114. https://doi.org/10.1017/S0021859610000997

Lugtenberg B, Kamilova F (2009) Plant-growth-promoting rhizobacteria. Annu Rev Microbiol 63:541–556

Mansfield JW (2000) Antimicrobial compounds and resistance. In: Mechanisms of resistance to plant diseases. Springer, Dordrecht, pp 325–370

Marchner H (1995) Mineral nutrition of higher plants. Academic, San Diego

Mirzaee H, Shuey L, Schenk PM (2015) Transcriptomics of plants interacting with pathogens and beneficial microbes. In: Genomics, proteomics and metabolomics in nutraceuticals and functional foods, vol 4, pp 525–536

Mohammadi K, Sohrabi Y (2012) Bacterial biofertilizers for sustainable crop production: a review. J Agric Biol Sci 7:307–316

Mueller UG, Sachs JL (2015) Engineering microbiomes to improve plant and animal health. Trends Microbiol 23(10):606–617

Murray-Kolb LE (2013) Iron and brain functions. Curr Opin Clin Nutr Metab Care 16(6):703–707

Nannipieri P, Ascher J, Ceccherini MT, Landi L, Pietramellara G, Renella G (2003) Microbial diversity and soil functions. Eur J Soil Sci 54:655–670

Nkomoki W, Bavorová M, Banout J (2018) Adoption of sustainable agricultural practices and food security threats: effects of land tenure in Zambia. Land Use Policy 78:532–538. https://doi.org/10.1016/j.landusepol.2018.07.021

Oerke EC, Dehne HW (2004) Safeguarding production—losses in major crops and the role of crop protection. Crop Prot 23(4):275–285

Padmanabhan SY (1973) The great Bengal famine. Annu Rev Phytopathol 11(1):11–24

Pal KK, Gardener BM (2006) Biological control of plant pathogens. The Plant Health Instructor. https://doi.org/10.1094/PHI-A-2006-1117-02

Pandey G (2018) Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India. Environ Technol Innov 11:299–307. https://doi.org/10.1016/j.eti.2018.06.012

Pieterse CM, Zamioudis C, Berendsen RL, Weller DM, Van Wees SC, Bakker PA (2014) Induced systemic resistance by beneficial microbes. Annu Rev Phytopathol 52:347–375

Pimentel D, McNair S, Janecka J, Wightman J, Simmonds C, O'connell C, Wong E, Russel L, Zern J, Aquino T, Tsomondo T (2001) Economic and environmental threats of alien plant, animal, and microbe invasions. Agr Ecosyst Environ 84(1):1–20

Prasad R, Kumar M, Varma A (2015) Role of PGPR in soil fertility and plant health. In: Plant-growth-promoting rhizobacteria (PGPR) and medicinal plants. Springer, Cham, pp 247–260

Prashar P, Kapoor N, Sachdeva S (2014) Rhizosphere: its structure, bacterial diversity and significance. Rev Environ Sci Biotechnol 13:63–77

Rana A, Joshi M, Prasanna R, Shivay YS, Nain L (2012) Biofortification of wheat through inoculation of plant growth promoting rhizobacteria and cyanobacteria. Eur J Soil Biol 50:118–126

Rangasamy K, Athiappan M, Devarajan N, Samykannu G, Parray JA, Aruljothi KN, Shameem N, Alqarawi AA, Hashem A, Abd_Allah EF (2018) Pesticide degrading natural multidrug resistance bacterial flora. Microb Pathog 114:304–310

Rasmann S, Turlings TC (2016) Root signals that mediate mutualistic interactions in the rhizosphere. Curr Opin Plant Biol 32:62–68

Roberts MJ, Schimmelpfennig DE, Ashley E, Livingston MJ, Ash MS, Vasavada U (2006) The value of plant disease early-warning systems: a case study of USDA's soybean rust coordinated framework

Rousk J, Baath E, Brookes PC, Lauber CL, Lozupone C, Caporaso JG, Knight R, Fierer N (2010) Soil bacterial and fungal communities across a pH gradient in an arable soil. ISME J 4:1340–1351

Sahu PK, Singh DP, Prabha R, Meena KK, Abhilash PC (2018) Connecting microbial capabilities with the soil and plant health: options for agricultural sustainability. Ecol Indic. https://doi.org/10.1016/j.ecolind.2018.05.084

Salgueiro MJ, Zubillaga M, Lysionek A, Cremaschi G, Goldman CG, Caro R, De Paoli T, Hager A, Weill R, Boccio J (2000) Zinc status and immune system relationship. Biol Trace Elem Res 76(3):193–205

Sandhya V, Ali SZ, Grover M, Reddy G, Venkateswarlu B (2009) Alleviation of drought stress effects in sunflower seedlings by the exopolysaccharides producing Pseudomonas putida strain GAP-P45. Biol Fertil Soils 46:17–26

Saravanan VS, Subramoniam SR, Raj SA (2004) Assessing in vitro solubilization potential of different zinc solubilizing bacterial (ZSB) isolates. Braz J Microbiol 35(1–2):121–125

Savary S, Ficke A, Aubertot JN, Hollier C (2012) Crop losses due to diseases and their implications for global food production losses and food security. Food Sec 4(4):519–537

Scandalios JG (1994) Regulation and properties of plant catalases. In: Foyer CH, Mullineaux PM (eds) Causes of photo-oxidative stress and amelioration of defense systems in plants. CRC, Boca Raton, pp 275–316

Schloss PD, Handelsman J (2006) Toward a census of bacteria in soil. PLoS Comput Biol 2:e92

Selvakumar G, Panneerselvam P, Ganeshamurthy AN (2012) Bacterial mediated alleviation of abiotic stress in crops. In: Bacteria in agrobiology: stress management. Springer, Berlin, Heidelberg, pp 205–224

Sgherri CLM, Maffei M, Navari-Izzo F (2000) Antioxidative enzymes in wheat subjected to increasing water deficit and rewatering. J Plant Physiol 157:273–279

Sharma SK, Ramesh A, Sharma MP, Joshi OP, Govaerts B, Steenwerth KL, Karlen DL (2010) Microbial community structure and diversity as indicators for evaluating soil quality. In: Lichtfouse E (ed) Biodiversity, biofuels, agroforestry and conservation agriculture, vol 5. Sustainable Agriculture Reviews, Springer, Netherlands, pp 317–358

Sharma P, Aggarwal P, Kaur A (2016) Biofortification: a new approach to eradicate hidden hunger. Food Rev Int 33(1):1–21

Shaw LJ, Morris P, Hooker JE (2006) Perception and modification of plant flavonoid signals by rhizosphere microorganisms. Environ Microbiol 8(11):1867–1880

Shoda M (2000) Bacterial control of plant diseases. J Biosci Bioeng 89(6):515–521

Singh DK (2008) Biodegradation and bioremediation of pesticide in soil: concept, method and recent developments. Indian J Microbiol 48(1):35–40

Singh AV, Prasad B, Goel R (2018) Plant growth promoting efficiency of phosphate solubilizing Chryseobacterium sp. PSR 10 with different doses of N and P fertilizers on Lentil (Lens culinaris var. PL-5) growth and yield. Int J Curr Microbiol App Sci 7(05):2280–2289

Srivastava MP, Tewari R, Sharma N (2013) Effect of different cultural variables on siderophores produced by Trichoderma spp. Int J Adv Res 1:1–6

Sturz AV, Christie BR (2003) Beneficial microbial allelopathies in the root zone: the management of soil quality and plant disease with rhizobacteria. Soil Tillage Res 72(2):107–123

Subbarao NS (1988) Phosphate solubilizing microorganism. In: Biofertilizer in agriculture and forestry. Regional Biofert. Dev. Centre, Hissar, India, pp 133–142

Subramanian KS, Tenshia V, Jayalakshmi K, Ramach V (2009) Role of arbuscular mycorrhizal fungus (Glomus intraradices)(fungus aided) in zinc nutrition of maize. J Agric Biotechnol Sustain Dev 1(1):029–038

Tang C, Komai K, Huang R (1989) Allelopathy and the chemistry of the rhizosphere. Phytochem Ecol 9

Tang J, Liu LX, Hu SF, Chen YP, Chen J (2009) Improved degradation of organophosphate dichlorvos by Trichoderma atroviride transformants generated by restriction enzyme mediated integration (REMI). Bioresour Technol 100:480–483

Tatum L (1971) The southern corn leaf blight epidemic. Science 171:1113–1116

Tester M, Davenport R (2003) Na+ tolerance and Na+ transport in higher plants. Ann Bot 91(5):503–527

Timmusk S, Wagner GH (1999) The plant-growth-promoting rhizobacterium Paenibacillus polymyxa induces changes in Arabidopsis thaliana gene expression: a possible connection between biotic and abiotic stress responses. Mol Plant Microbe Interact 12:951–959

Trivedi P, Schenk PM, Wallenstein MD, Singh BK (2017) Tiny microbes, big yields: enhancing food crop production with biological solutions. J Microbial Biotechnol 10(5):999–1003

Ullstrup A (1972) The impacts of the southern corn leaf blight epidemics of 1970–1971. Annu Rev Phytopathol 10:37–50

United Nations System Standing Committee on Nutrition (UNSSCN) (2004) 5th report on the world nutrition situation nutrition for improved development outcomes. SCN, Geneva

Valverde A, De Maayer P, Oberholster T, Henschel J, Louw MK, Cowan D (2016) Specific microbial communities associate with the rhizosphere of Welwitschia mirabilis, a living fossil. PLoS One 11(4):e0153353

Vorholt JA (2012) Microbial life in the phyllosphere. Nat Rev Microbiol 10(12):828

Walter GH, Chandrasekaran S, Collins PJ, Jagadeesan R, Mohankumar S, Alagusundaram K, Ebert PR, Daglish GJ, Nayak MK, Mohan S, Srivastava C (2016) The grand challenge of food security: general lessons from a comprehensive approach to protecting stored grain from insect pests in Australia and India. Indian J Entomol 78:7–16

Wandersman C, Delepelaire P (2004) Bacterial iron sources: from siderophores to hemophores. Annu Rev Microbiol 58:611–647

Wani SP (1990) Inoculation with associative nitrogen fixing bacteria: role in cereal grain production improvement. Indian J Microbiol 30:363–393

Welbaum GE, Sturz AV, Dong Z, Nowak J (2004) Managing soil microorganisms to improve productivity of agro-ecosystems. Crit Rev Plant Sci 23(2):175–193

Whitelaw MA (2000) Growth promotion of plants inoculated with phosphate solubilizing fungi. Adv Agron 69

Whiting SN, de Souza MP, Terry N (2001) Rhizosphere bacteria mobilize Zn for hyperaccumulation by Thlaspi caerulescens. Environ Sci Technol 35(15):3144–3150

Yang J, Kloepper JW, Ryu CM (2009) Rhizosphere bacteria help plants tolerate abiotic stress. Trends Plant Sci 14:1–4

Yin B, Crowley D, Sparovek G, De Melo WJ, Borneman J (2000) Bacterial functional redundancy along a soil reclamation gradient. Appl Environ Microbiol 66:4361–4365