Microbe-Mediated Reclamation of Contaminated Soils: Current Status and Future Perspectives

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10.1 Introduction

Soil is the major life-supporting natural resource for plant growth and crop productivity. It is assumed that approximately 30% of land is degraded or polluted by several anthropogenic activities and this proportion is continuously increasing globally (Abhilash et al. 2012). Today, different pollutants, e.g., heavy metals, salts, pesticides, and organic pollutants, pose serious threats to arable lands (Dixit et al. 2015). These toxic materials are harmful for agricultural system; moreover, they cause serious toxicity to life when they are added to the environment through different agricultural practices (Sarwar et al. 2017). Environmental contamination of heavy metals is caused by many sources including medical waste; combustion of leaded batteries; fertilizers, coal, and petrol combustion; smelting; industrializations; and mining (Liu et al. 2018). Heavy metals adversely affect plant growth by hindering the photosynthetic process. Toxic metals also decrease the leaf water content, transpiration rate, and stomatal conductance by reducing the number and size of xylem vessels in plants (Nagajyoti et al. 2010; Ruperao et al. 2014). These heavy metals also contaminate the food chain through their accumulation in the edible portion of the plants. Hence, it is necessary to eliminate these metals from agro-ecosystem to attain a sustainable yield and ecological safety. In agro-ecosystems, beneficial microorganisms are known to play an important function in the

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reclamation of heavy metal-contaminated soil by triggering the stress-tolerant mechanisms in plants (Akram et al. 2016).

Under stress conditions, plants utilize various physiological and morphological mechanisms to neutralize the heavy metal stress. The sensitive and resistant crops have different stress tolerance levels (Chaves et al. 2009; Munns 2002). A variety of microorganisms are found to develop an interaction with crop plants in soil. However, their diversity is different for rhizosphere and bulk soil because of the presence of different mechanisms of adaptation in crop plants. Crop plants generally develop a healthy plant microbe interaction from the available soil microbiome (Miransari 2017; Sobariu et al. 2017). A broad range of beneficial microbes including plant growth-promoting rhizobacteria (PGPRs) and arbuscular mycorrhizal fungi (AMF) have ability to develop a symbiotic or non-symbiotic association with host plant to improve the plant growth (Shahid et al. 2017). The coordination mechanisms are important in order to develop symbiotic association between the microbes and host plant (Shahid et al. 2017).

Presence of microorganisms in the soil is important for alleviation of stress effect in contaminated soils. For example, soil biochemical properties are positively affected by different microbial metabolites such as polysaccharides, organic acids, enzymes, osmolytes, etc. (Miransari 2017). Plenty of interactions occur in the interactive microenvironment of the soil and plant between the soil-inhabiting microbes and the plants affecting the physicochemical and biological characteristics of the soil. Various plant beneficial microbes have the ability to promote plant growth and development by various mechanisms of direct and indirect nature, including increased nutrients and water uptake, synthesis of various phytohormones, alleviation of stress, and siderophore production (Jha and Subramanian 2018; Mittal et al. 2017; Novo et al. 2018). Several physical, biological, and chemical practices can also be utilized for the remediation of the metal- and salt-contaminated soils. But microbe-mediated methods have emerged as cost-efficient and environmental friendly methods. This approach is one of the significant approaches for decontamination of soils, specifically in case of metal and salt contamination (Sarwar et al. 2017).

This chapter discusses about the impact of heavy metals and salts in the agro-ecosystems and effective microbial processes used for the reclamation of these contaminated soils.

10.2 Contaminated Soils

Worldwide, the soil is mostly contaminated with metal ions, salts, and organic residues due to urbanization and weathering processes (Cristaldi et al. 2017). Due to industrial revolution, the amount of metals in soil has increased exponentially (Alloway 2013). The heavy metals are naturally found throughout the earth's crust, but many heavy metals like metalloid mercury (Hg), cadmium (Cd), zinc (Zn), arsenic (As), chromium (Cr), nickel (Ni), lead (Pb), and copper (Cu) are mostly utilized in different industrial processes and subsequently discharged into the environment as a waste (Alloway 2013; Cristaldi et al. 2017). Wastewater from the tanneries carrying many malodorous chemical materials such as ammonia, dyes, and hydrogen sulfide is discharged into the agricultural soils, especially in the areas adjacent to cities (Karabay 2008). In addition, petrochemical industries and other vehicles release numerous metals into the environment (Manno et al. 2006). Similarly, soils have also been contaminated with sodium salts due to the water logging and excessive salt runoff from nearby areas.

10.3 Types of Contaminated Soils

Generally, contamination can be categorized based on the source of the contaminant. Mostly, the point of the contamination is related to the improper disposal of the waste, industrial effluents, and accidental spillage of toxic materials during transportation (Valentín et al. 2013). Few domestic and industrial sources of contamination are usage of septic tanks in an inconsiderate way, leakage of the underground oil tanks, and industrial effluents. Diffuse contamination is related to the agricultural practices, improper waste disposal, spillage during transportation, forestry, and management of wastewater (Loehr 2012; Valentín et al. 2013). Contamination of the soil is mostly connected with the contamination of the groundwater. Water in the soil pores moves in a vertical way at the rate mainly driven by soil texture (Mulligan et al. 2001). In contrast, the flow of horizontal groundwater is determined by the lakes and rivers. Transportation of several water-soluble contaminants is carried out by the horizontal and the vertical flow of the groundwater. Contamination of groundwater is much problematic and expensively managed. So, it is important to avoid the seepage of the contaminants into the underground water resources (Meffe and de Bustamante 2014). Furthermore, the chemicals that are insoluble in water also influence the higher organisms as a component of biodegradable lipophilic compounds that have tendency to gather in food chain (Duruibe et al. 2007).

10.4 Agriculture in Contaminated Soils

Agricultural productivity is adversely affected by the discharge of the industrial effluents as well as by the heavy metals and salts. Stresses due to the salinity and heavy metals suppress the plant growth and result in a decrease in yield (Nicholson et al. 2003). For plant survival, these abiotic stresses must be suppressed or plants must be able to tolerate these stresses (Vimal et al. 2017). The stresses affect the plant growth by producing nutritional and the hormonal imbalance together with some physiological disorders like abscission, senescence, epinasty, and vulnerability to diseases (Nicholson et al. 2003). In stressed conditions, plant produces high levels of ethylene (C_2H_4) which negatively affects the growth and health of the plant (Vimal et al. 2017). Furthermore, the factors that limit the germination, seedling vigor, and agricultural productivity are frequently found in arid and semiarid regions of the world (Amato et al. 2014). High levels of salts, organic residues, and heavy metals can cause a disparity of the cellular ions, resulting in osmotic stress, ion toxicity, and synthesis of reactive oxygen species (ROS) (Rodríguez-Serrano et al. 2009; Tuteja 2007). The abiotic stresses directly influence the biochemical and physiological properties and decrease plant productivity.

10.5 Significance of Microbes in Contaminated Soils

Plant-associated microbes have a proficient role in nutrient recycling and alleviation of stress consequences (Abriouel et al. 2011; Burd et al. 2000). Recent studies depicted the importance of plant-associated microbes in conferring stress tolerance in plants. The successful colonization of PGPR and AMF with host plants results in better nutrient acquisition and improved plant biomass under stress conditions. It is indicated that heavy metals hinder the uptake of other metals and nutrients essential for plant growth like Fe, Ca, P, and Zn and thus retard the plant growth (Glick 2010). Under such circumstances, plant-associated microbes are known to enhance the plant nutrition by mobilization of fixed nutrients, thus making these accessible to the plant roots. The N_2 fixation by rhizobacterial genera such as *Mesorhizobium*, *Rhizobium*, and *Bradyrhizobium* may contribute to enhance the growth of the legume crops in metal-contaminated and salt-affected soils by providing N to plants (Adams et al. 2004; Geddes et al. 2015). The improved P uptake is also reported after treatment of crops with phosphate-solubilizing microbes (Rajkumar et al. 2012). Moreover, siderophore-producing microbes have the ability to provide plants with iron under iron scarcity. Previous studies showed that plants inoculated with ACC deaminase-producing microbes have better germination and growth of seedlings due to the reduced ethylene concentration under abiotic stress conditions (Rodriguez et al. 2008). Madhaiyan et al. (2007) described that tomato seeds treated with ACC deaminase-containing *Methylobacterium oryzae* showed improved growth when grown in soils contaminated with Ni and Cd than non-inoculated plants. The microbes decreased the synthesis of ethylene under heavy metal-induced stress via ACC deaminase activity (Ali et al. 2014; Madhaiyan et al. 2007). Some studies also reported the presence of the cumulative influence of microbes on the plant growth under stressed environmental conditions (Li et al. 2014; Meffe and de Bustamante 2014).

10.5.1 Role of Microbes in Bioremediation

The plant growth and productivity, in salt- and metal-contaminated lands, is influenced by a diverse group of microorganisms having the ability to endure high metal concentration and confer stress tolerance on plants (Zhuang et al. 2007). Many PGPRs and AMF have been found to remove salts, organic residues, and heavy metals from contaminated soils. They improve the plant growth and soil health by a variety of mechanisms such as metal bioavailability, bioleaching, biotransformation, biovolatilization, bioaccumulation, release of chelators such as siderophores, ACC deaminase activity, solubilization of inorganic phosphate, exopolysaccharide synthesis, nitrogen fixation, phytohormones production, etc. (Fig. 10.1) (Barriuso et al. 2008; Bhattacharyya and Jha 2012; Gupta and Verma 2015; Novo et al. 2018). Table 10.1 describes the microbial species, their metabolites, and mechanisms of heavy metal bioremediation.

10.5.2 Role of Microbes in Plant Growth Promotion

10.5.2.1 Nitrogen Fixation

The essential plant nutrients have important role in ameliorating the heavy metal-induced toxicity in plants. Nitrogen (N) is the main constituent of many biomolecules like vitamins, proteins, hormones, and nucleic acids and thus essential for plant growth (Defez et al. 2017). Nitrogen supply increases tolerance against heavy metals in plants by improving the activity of ribulose 1,5-bisphosphate carboxylase as well as photosynthetic capacity (Ahmad et al. 2016; Rajkumar et al. 2012). Sufficient level of N is required by plants to tolerate the heavy metals in the form of N metabolites (Schutzendubel and Polle 2002). Several PGPRs and AMF have potential to fix atmospheric nitrogen and improve nitrogen availability to plants. PGPRs and AMF strains *Klebsiella mobilis* and *Glomus mosseae* have been reported to tolerate heavy metals and improve the grain yield (Meng et al. 2015; Pishchik et al. 2002; Rajkumar

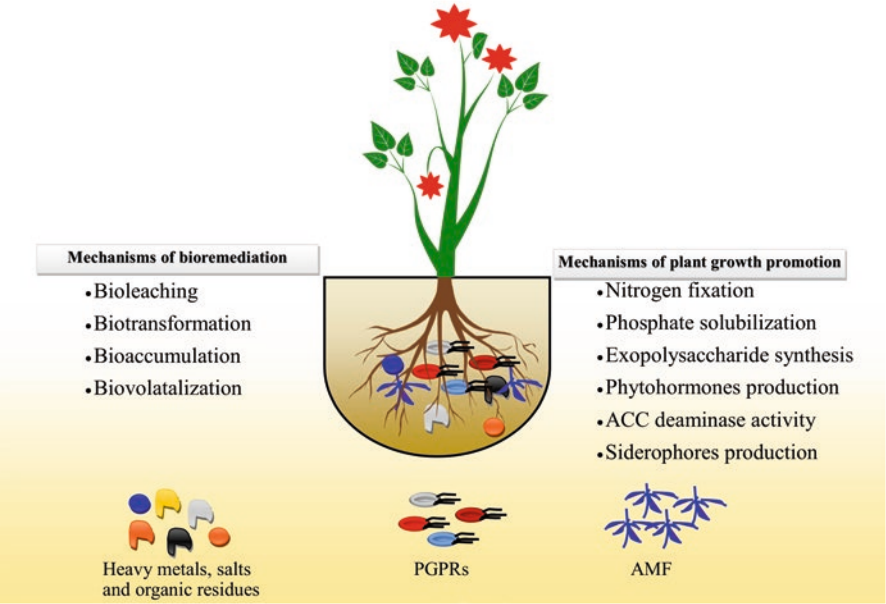

Fig. 10.1 Schematic representation of mechanisms involved in bioremediation and plant growth promotion

Table 10.1 Microorganisms and their reported mechanisms involved stress alleviation and plant growth promotion in contaminated soils

Microorganisms	Plant	Heavy metals	Mechanism	References
Azotobacter chroococcum HKN-5 *Bacillus megaterium* HKP-1	*Brassica juncea*	Lead and zinc	Nitrogen fixation, phosphate solubilization, and potassium solubilization	Niu et al. (2006)
Pseudomonas sp.	*Brassica napus*	Cadmium	IAA production	Sheng and Xia (2006)
Methylobacterium oryzae	*Lycopersicon esculentum*	Cadmium	ACC deaminase activity, bioaccumulation, and biotransformation	Madhaiyan et al. (2007)
B. edaphicus	*Brassica juncea*	Lead	Siderophore production	Sheng et al. (2008)
Streptomyces tendae F4	*Helianthus*	Cadmium	Siderophore production	Dimkpa et al. (2009)
S. acidiscabies E13	*Vigna unguiculata*	Copper, iron, and magnesium	Siderophore production	Dimkpa et al. (2009)
B. cereus	*Trifolium repens*	Iron, magnesium, zinc, and cadmium	IAA production, siderophore production, and bioleaching	Azcón et al. (2010)
Bacillus sp. SLS18	*Sweet sorghum*	Cadmium	IAA production, ACC deaminase, and siderophore production	Couillerot et al. (2011)
Agrobacterium radiobacter	*Populus deltoides*		IAA production and siderophore production	Cui et al. (2011)
Pseudomonas sp.	*Alyssum serpyllifolium*	Nickel	Phosphate solubilization, IAA production, ACC deaminase, and siderophore production	Abriouel et al. (2011)
P. aeruginosa OSG41	*Cicer arietinum*	Chromium	Phosphate solubilization, IAA production, ACC deaminase, and siderophore production	Oves et al. (2013)
Bradyrhizobium sp.	*Glycine max*	Cadmium	Siderophore production	Guo and Chi (2014)
Bacillus sp. SC2b	*Brassica napus*	Lead, zinc, and cadmium	Phosphate solubilization, exopolysaccharides production, and IAA production	Ahemad (2015)
Paecilomyces lilacinus NH 1	*Solanum nigrum* L	Cadmium	Antioxidative defense system	Gao et al. (2010)
Glomus etunicatum	*Glycine max*	Manganese	Siderophore production and biovolatilization	Nogueira et al. (2007)
G. mosseae	*Cajanus cajan*	Lead, and cadmium	Biosorption	Garg and Aggarwal (2011)
G. clarum and *Gigaspora margarita*	*Coffea arabica*	Copper and zinc	Nutrient acquisition	Andrade et al. (2010)

et al. 2012). Similarly, nitrogen fixation by soil microbes provided Cd tolerance to *Glycine max* through enhanced photosynthesis and decreased levels of heavy metals when grown in contaminated soil (Guo and Chi 2014).

10.5.2.2 Phosphate Solubilization

One of the important characteristics of phosphate-solubilizing microbes is to convert the unavailable inorganic and organic phosphate into the forms which are accessible to the plant (Chen et al. 2006; Qiu et al. 2011). Phosphate-solubilizing microbes are indigenous to all types of environment such as bulk and rhizosphere soils, soil rock phosphate dumping site, phyllosphere, rhizoplane, and stressed soils (Ahemad 2015). Phosphate-solubilizing microbes help in mobilization of unavailable soil phosphates chelated to metal ions (e.g., Fe-P, Ca-P, and Al-P) and increase the phosphate availability to plants (Etesami 2018). The known mechanism of solubilization of soil phosphates is the synthesis of organic acids, lowering the pH of surroundings and, subsequently, detaching the bound phosphates (Sharma et al. 2013; Kumar and Shastri 2017; Qiu et al. 2011). The available phosphate rapidly stops the mobilization of salt and heavy metals from soil to plant and increase the plant's ability to resist metals through the production of non-soluble complexes with heavy metals (Etesami 2018). It is concluded that both PGPR and AMF help plants to alleviate heavy metal and salt stress through the process of phosphate solubilization. Soil microbes enhance the plant growth by phosphate uptake after inoculation. Species such as *Rhizophagus irregularis*, *Pseudomonas* sp. (wheat), *Pantoea* J49 (peanut), and *Psychrobacter* sp. (sunflower) are reported to improve plant growth through phosphate solubilization under stressed environments (Rajkumar et al. 2012; Taktek et al. 2015).

10.5.2.3 Exopolysaccharides Synthesis

Exopolysaccharides (EPS) are carbohydrate polymers that are produced by rhizobacteria (Dhole et al. 2015). They form a capsule layer on the cell wall or act as a slime layer when released from the cell. In bacteria, EPS perform variety of functions including maintenance of cellular functions, production of biofilms, antibacterial activity, protection of bacteria from dry environment, gelling, and bioremediation activity (Bogino et al. 2013; Costerton et al. 2003). The production of EPS is directly associated with stress alleviation. The EPS-producing bacteria improve plant growth and development under stressed environment. In a study, wheat plants showed improved growth when inoculated with exopolysaccharide-producing bacteria belonging to *Bacillus* and *Enterobacter* genera in contrast to non-inoculated plants. However, the mechanism of EPS synthesis and their stimulatory effect on plant growth under saline environment is not well understood (Chen et al. 2016). The strains like *Bacillus subtilis*, *Pseudomonas aeruginosa,* and *Streptococcus mutans* have been best known for their exopolysaccharide production potential (Chen et al. 2016; Vimala and Lalithakumari 2003).

10.5.2.4 Phytohormone Production

Phytohormones (auxins, gibberellins, and cytokinins) produced by soil microbes are the direct plant growth-promoting agents under salinity and heavy metal stress conditions (Nagel et al. 2017). Under heavy metal and salt stress, plant cells start producing ROS which further induce the MAP kinase (MAPK) signalling pathway (Abdel-Lateif et al. 2012; Passari et al. 2016). The heavy metal-induced stress interrupts auxin physiology in *Arabidopsis* and poplar through decrease in auxin levels (Elobeid et al. 2011). Soil microbes that produce indole-3-acetic acid (IAA) can prevent the negative effects of heavy metals on plant development. Under Cd stress, rhizobacteria such as *Agrobacterium radiobacter, Azospirillum lipoferum*, *Flavobacterium* sp., and *Arthrobacter mysorens* were able to produce IAA and improve the development and growth of barley (Azcón et al. 2010; Gontia-Mishra et al. 2016). IAA reduces the toxicity caused by heavy metals in plants by decreasing heavy metal translocation and sorption or by enhancing the antioxidative enzymatic machinery. The root growth and development induced by auxins help in nutrient acquisition and root proliferation (Passari et al. 2016).

10.5.2.5 ACC Deaminase Activity

At a high concentration, ethylene has negative effects on plants in terms of reduced root and shoot proliferation (Ali et al. 2014; Etesami 2018). The stressed environment stimulates the production of 1-aminocyclopropane-1-carboxylate (ACC) which is the ethylene precursor. A bacterial enzyme ACC deaminase has a substantial potential to promote plant growth under heavy metal and salt stress due to its ability to cleave ACC into ammonia and α-ketobutyrate (Ali et al. 2014; Glick et al. 2007). The production of ACC deaminase by PGPRs and AMF is the fundamental mechanism to cope with the environmental stresses, especially the heavy metals and salts stress conditions (Glick 2005). The ACC deaminase producing PGPR are native to various soil environments and can act as ACC reservoir for maintaining the optimum level of ethylene required for the normal plant growth. The microbes are responsible for proliferation of root system in plants in order to acquire more nutrients to ameliorate abiotic stress (Frazier et al. 2011). In general, various studies have reported the proficient role of ACC deaminase-producing microbes (PGPRs and AMF) in improving plant growth in heavy metal- and salt-contaminated soils (Etesami 2018). The widely studied species of ACC deaminase-producing microbes are *Pseudomonas* sp., *M. oryzae, P. brassicacearum, P. fluorescens, P. koreensis, E. aerogenes, Achromobacter*, *B. megaterium, Burkholderia* sp., *Actinobacteria* sp., and *G. mosseae*, etc. (Etesami 2018; Rajkumar et al. 2012). To screen the best microbe for ameliorating stress in plants grown in heavy metals and salt contaminated soils, it's recommended that they are initially investigated for their ACC deaminase producing potential (Glick 2010).

10.5.2.6 Siderophore Production

Iron (Fe) is one of the most important elements for the normal plant growth and to carry out the healthy plant and microbial cellular activities specifically during heavy metal and salt stress (Parida et al. 2003). Berg et al. (2002) indicated that high levels of heavy metals and salt within plant body negatively affect the biosynthesis of chlorophyll and decrease the Fe uptake by the plant. Plants contain mechanisms to survive in Fe-deficient environment and enhance the Fe uptake either through acidification of rhizosphere or through the synthesis of phytosiderophores. Some rhizospheric microbes including PGPRs and AMF are known to provide plant with Fe by producing siderophores (low molecular weight Fe-chelating secondary metabolites) (Glick 2010; Rajkumar et al. 2010). It has been documented that in contrast to phytosiderophores, the microbe-oriented siderophores have high metal chelating ability. Therefore, the PGPRs and AMF may prove to be the solution of metal solubilization to improve the efficacy of plants (Rajkumar et al. 2010). Studies suggested that siderophore-producing microbes should improve the chlorophyll content and growth of the plant under metal-contaminated conditions by triggering the mobilization of Fe from heavy metal cations complex. Another study reveals that siderophore-producing microbes (SPM) have the ability for chlorophyll production in plant by provision of additional Fe and N (Rasouli-Sadaghiani et al. 2010). It is recognized that SPM have the capability to save plants against heavy metal toxicity. The reported PGPR strains involved in the production of siderophores are *P. fluorescens* and *P. putida*, whereas siderophore-producing AMF mostly belong to genus *Aspergillus*. These SPM can improve the nutrient status of the plant under heavy metal-induced stress conditions (Machuca and Milagres 2003; Rajkumar et al. 2012).

10.5.3 Role of Microbes in Stress Alleviation

The ameliorative role of soil microbes against stressed environments has been well documented. The soilborne microbial community improves the soil structure by producing exopolysaccharides (EPS), osmolytes, stress-related proteins, etc. The diverse interactions in plant rhizosphere positively affect the biological and physicochemical characteristics of the soil (Flemming and Wingender 2010; Singh and Satyanarayana 2011). The EPS-producing microbes have the potential to improve the soil structure by increasing the macropore volume within soil and aggregation of rhizospheric soil. This helps the plants to uptake more water and nutrients from soil under stress conditions. The mycorrhizal hyphae anchor deeply into the soil micropores and improve the nutrient and water availability to host plants under stressed environments (Sandhya et al. 2009a, b). The PGPRs also harbor the substantial potential to mitigate stress and plant growth promotion by producing ROS scavenging enzymes (Berg 2009; Grover et al. 2011). Microbes generally use different mechanisms to alleviate soil stress. Various mechanisms of heavy metal stress alleviation are known such as bioleaching, biotransformation, bioaccumulation, biovolatilization, etc. (Fig. 10.1). Microorganisms utilize heavy metals present in soil as chemicals for their own growth and development (Gupta and Verma 2015; Novo et al. 2018). The role of AMF and PGPRs in stress mitigation is described below.

10.5.3.1 Role of AMF in Stress Alleviation

The AMF are capable of improving the host plant growth under abiotic stress conditions. Various mechanisms that are employed by mycorrhizal fungi to enhance the growth of the plants under stress conditions are diverse hyphal framework, phytohormone synthesis, interactions with the neighboring microbes, etc. (Miransari 2017). The alleviating role of AMF under salinity in different crops has been widely investigated. It is reported that increased proline production, phosphorous uptake, and high sugar concentration provided plants with enhanced tolerance against induced salt stress (Daei et al. 2009; Garg and Singla 2016; Talaat and Shawky 2014). Previous studies showed the beneficial effects of mycorrhizal fungi, especially the species belonging to the genus *Glomus,* on plants under numerous stresses such as water logging, heavy metals, low temperature, salinity, drought, compaction, and acidity. The strains of *G. intraradices, Trichoderma koningii*, and *G. deserticola* were found to enhance the heavy metal tolerance in various crop plants like corn, tomato, eucalyptus, and *Medicago tranculata*. Nogueira et al. (2007) reported that inoculated *Glycine max* plants with *G. etunicatum* and *G. macrocarpum* exhibit better growth and P content than the control plants when grown in heavy metal-contaminated soil. The fungal hyphae can penetrate into fine micropores where plant roots are unable to grow and provide more water and nutrients to the host plant. Under compaction of soil, this feature promotes the plant growth and development (Garg and Chandel 2010; Miransari 2017). The plant growth is improved by AMF under drought and osmotic stress due to different mechanisms such as induction of antioxidative enzymatic machinery (i.e., catalases, superoxide dismutases, and peroxidases), limiting the malondialdehyde (MDA) synthesis, increase in the non-structural carbohydrate content, and high uptake of Ca^{+2}, Mg^{+2}, and K^+ (Wu and Xia 2006).

10.5.3.2 Role of PGPR in Stress Alleviation

It has been reported that PGPRs have growth-promoting effects on plants under stress ambience. To mitigate stress and promotion of plant growth, PGPRs use various mechanisms such as modification in plant structure and function, synthesis of phytohormones, high proline content, improved nutrient uptake, maintenance of low ethylene level by ACC deaminase activity, and interaction with soil microbiota (Miransari 2014). The ameliorative effects of *Azospirillum* spp. and *Rhizobium* spp. against drought and salinity have been extensively investigated (Arzanesh et al. 2011; Hamaoui et al. 2001). Ali et al. (2009) reported that *Pseudomonas* spp. strain AMK-P6-treated sorghum plants showed improved thermotolerance than non-inoculated plants under induced heat stress. The PGPRs are also reported to boost antioxidative defense mechanisms in plants due to the upregulation of stress-responsive genes to cope with abiotic stress conditions (Chakraborty et al. 2015; Akram et al. 2016; Shahid et al. 2019). The PGPRs resist various stresses by enhancing the K^+ ion uptake along with the accumulation of other solutes like polyols, amino acids, saccharides, and betaines. These solutes are either produced by bacteria or uptaken from its surroundings (Miransari 2017). It has been reported that *P. fluorescens* MSP-393 showed enhanced tolerance against salt stress by accumulating various solutes like aspartic acid, alanine, serine, glycine, glutamic acid, and threonine. Under stress, these solutes prevent proteins from denaturation (Paul and Nair 2008; Street et al. 2006). Moreover, PGPRs are capable of producing siderophores in the rhizosphere to enhance iron availability to plants under iron-deficient conditions. The PGPR-originated siderophores can reduce the heavy metal mobilization from contaminated soils and therefore can be utilized for soil reclamation purposes (Miransari 2017).

10.6 Current Perspectives of Microbes as Soil Reclamants

The exhaustive cropping systems have depleted the soil fertility and quality of arable lands. It is estimated that the intensive agricultural practices might convert the 30% of the world's total cultivated land to arid land by 2020 (Patel et al. 2015; Rashid et al. 2016). The decrease in soil fertility is one of the major global issues today. It can pose serious threats to crop cultivation and food security for the future generation. The agriculture system is mainly affected by the drastic changes in the environmental abiotic factors and reduction in the diversity and activities of soil microorganisms. The potential microbial populations can play pivotal roles to stabilize the degraded environment and agricultural soils (Patel et al. 2015; Singh 2015). The bacteria-releasing EPS have a significant role in the aggregation of rhizospheric soil under stressed conditions and is well documented. The microbially synthesized EPS in synergism with fungal hyphae stabilize the soil by forming macro- and micro-aggregates of soil particles (Grover et al. 2011; Nunkaew et al. 2015). The EPS-producing PGPR strains can also chelate cations such as Na^+, which enhance the ability of plant to survive under saline environmental conditions (Alami et al. 2000). Phytohormones of rhizobacterial origin induce certain physiological responses in the associated plants. The plant growth is enhanced by PGPR as a result of altering root morphology under abiotic stresses by producing different plant hormones like IAA, cytokinins, and gibberellic acid (Paul and Lade 2014). It has been revealed that wheat plants inoculated with IAA-producing *Streptomyces* showed enhanced growth than the control plants under induced salinity (Sadeghi et al. 2012).

The proliferating hyphal network of AMF helps plants to uptake water and mineral nutrients from the soil. The AMF-oriented glomalin (i.e., insoluble glycoprotein) stabilizes the soil structure by binding with macro- and micro-aggregates of soil particles (Li et al. 2015; Ortiz et al. 2015). The hyphal network of AMF not only facilitates plants in water and nutrient uptake but also restricts the heavy metal bioavailability to plants through biofiltration (Vimal et al. 2017). The restoration of agricultural land is associated with the efficient use of AMF and PGPR. The mixed culture of mycorrhizal fungi and bacteria was found to be more efficient in restoring soil fertility and organic matter profile in spite of their individual application (Rashid et al. 2016). However, extensive research insights are required in order to exploit microbial interactions for reconstructing the degraded agricultural lands.

10.7 Advantage of Microbes as Soil Reclamants

The economy of many developing countries depends on their agricultural production due to the significance of agriculture sector in those countries which provides food security, income, and employment to the people. However, poor soil fertility leads to soil erosion, lower crop yield, etc. Therefore, improvement of soil fertility is on the top of the development policy agenda list and should be dealt on a priority basis. Soil microbiota through various mechanisms like recycling of nutrients, regulation of soil organic matter, sequestration of carbon in soil, soil structure improvement, and enhancing the nutrient uptake efficiency and growth of plants contribute not only to improve the fertility status of soils but also sustainability of various ecosystems. Such services by soilborne microbes help in sustainability of the soil system along with the regulation of normal functioning of natural ecosystems (Singh et al. 2011). Microbiological reclamation of soil reduces the capital investment by improving resource utilization potential specifically cycling of nutrients, P bioavailability, N fixation, decomposition, and water uptake. The management of soil by microbes is an eco-friendly approach as it prevents land degradation and pollution by reducing the use of different chemical fertilizers. Hence, this microbe-based strategy improves crop productivity and quality by pest and disease controlling mechanisms, thus ensuring healthy food and food security for the continuously increasing population. Moreover, such techniques are helpful in the reclamation and restoration of non-fertile wastelands into fertile arable lands.

10.8 Problems in Microbe-Based Formulations

The potential application of microorganisms for various purposes (i.e., phytoremediation, bioremediation, bio-control, bio-fertilization, etc.) is directly associated with their capability to grow along with the native soil microbes and different environmental stresses in the field. Numerous reports are available indicating the efficient roles of microbes (i.e., PGPRs and AMF) in improving plant and soil health under stresses induced by various abiotic and biotic factors in laboratory and greenhouse experiments but are unable to display the same potential in the field conditions. For example, phosphate-solubilizing microbes were not found efficient under field experiments for phosphate solubilization but were found to be excellent P solubilizers under laboratory conditions (Compant et al. 2010; Gyaneshwar et al. 2002). Moreover, the beneficial activities of microorganisms have affected characteristics of the land, natural selection, and conventional agricultural practices such as crop rotation, application of agro-chemicals, and pesticides (Pishchik et al. 2002). The successful symbiotic association of microbial strains is based on the first-come-first-served principle. So, beneficial microbes must bypass others for their successful attachment with plant roots in order to help plants to grow under stressed environment. The bacteria are also present in the embryo or seeds of some weeds. These bacteria have to fight with other phyto-beneficial bacteria in soil. The successful establishment of plant beneficial bacteria directly depends on the uninterrupted supply of energy and carbon resources (Compant et al. 2010; Etesami and Maheshwari 2018). In field, the microbes that were found to be efficient under laboratory conditions have to compete with the natural soil microorganisms for nutrient uptake which limit their efficacy under natural environmental conditions. Furthermore, the microbiological soil management is also a time-consuming strategy because pre-selected microbes require time to adjust themselves according to the soil conditions. All the aforementioned limitations are required to be improved in the near future.

10.9 Future Prospects

Microorganisms help in the revitalization of nutrient-deficient soil and increase the growth and resistance of crop plants under various biotic and abiotic stress conditions. The complex and dynamic plant-microbe interactions affect plants as well as structural and physicochemical characteristics of soil under different stresses. The future of microbe-assisted reclamation of contaminated soil demands strong collaboration of bioremediation with nanobiotechnology (for improved remediation of affected soils), conventional biotechnology, and remediation of environmental stresses (such as nutrient scarcity and toxicity of contaminated site) through microbe-assisted phytoremediation. The remediation of contaminated soils using microbes can provide economical, agricultural, and environmental benefits to the world. However, it is difficult to achieve this goal.

Various challenges are also present that are not easy to handle, e.g., many contaminated lands require specific approaches and design for reclamation because of the uniqueness and complexity of the local conditions. However, we tried to summarize the roles and mechanisms of microorganisms that are used for remediation and reclamation purposes. Furthermore, nanotechnological and transgenic approaches due to their drastic environmental effects are not accepted publically. Fruitful research efforts are required to win the public interest and regulatory permission in order to implement these technologies on large scale. Till then, the conventional biotechnological techniques exploiting the interactions between soil microbiota and plant roots may serve for the remediation and reclamation of contaminated soils.

10.10 Conclusion

Microbe-based soil reclamation techniques present tremendous potential of implementing as alternatives or supplements to chemical solutions. More research investigations are needed to develop promising single strain or consortial bioinoculants for stressed soils in order to produce sustainable yield and improve soil health in a sustainable and cost-effective manner. Moreover, significant improvement in microbial strains, in terms of genetic and metabolic manipulations, is required to make the microbial solutions of polluted soils at par with the use of chemicals.

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