Microbe-Assisted Phytoremediation in Reinstating Heavy Metal-Contaminated Sites: Concepts, Mechanisms, Challenges, and Future Perspectives

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Abstract

Pollution has become a serious matter of environmental and political concerns in the world. Our natural environment has been contaminated by various organic and inorganic contaminants, which are being used in many industrial processes and released along with industrial effluents. Among them, heavy metals are highly toxic pollutants, which cause serious environmental pollution and severe health hazards in living beings, and there is a public outcry to ensure the safest and healthiest environment for living beings. Phytoremediation, a type of bioremediation, has been emerged as an eco-sustainable technology that uses plants and their associated microbes to clean up heavy metal-contaminated soils, water, and wastewaters as compared to various physicochemical remediation technologies currently being applied for environmental restoration. However, in current scenario, phytoremediation assisted by plant-associated microorganisms, i.e., microbe-assisted phytoremediation (use of microbes, i.e., plant growth-promoting rhizobacteria, endophytes, and arbuscular mycorrhizal fungi, in assisted phytoremediation), is highly preferred for the remediation of heavy metal-contaminated sites as they have potential to alleviate the heavy metal toxicity in plants through their own metal resistance system and facilitate and

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improve the growth of host plants under heavy metal stress. In this line, this chapter aims to provide an overview on microbe-assisted phytoremediation, illustrate various mechanisms elicited for plant growth promotion and heavy metal phytoremediation (accumulation/detoxification), and discuss drawbacks and future challenges.

Keywords
Heavy metals · Environmental pollution · Toxicity · Microbe-assisted phytoremediation · Contaminated sites

6.1 Introduction

Environmental pollution is of serious ecological concern worldwide with a continually rising public outcry to ensure the safest and healthiest environment. A variety of organic and inorganic pollutants have been reported to cause environmental pollution and severe health hazards in living beings (Maszenan et al. 2011; Saxena and Bharagava 2017). Among them, heavy metals (HMs) are highly notorious pollutants due to their high abundance and nonbiodegradable and persistent nature in the environment. Hence, they cause soil/water pollution and toxic, genotoxic, teratogenic, and mutagenic effects in living beings (Dixit et al. 2015; Sarwar et al. 2017). They also cause endocrine disruption and neurological disorders even at low concentration (Yadav 2010; Maszenan et al. 2011; Dixit et al. 2015; Sarwar et al. 2017). Any naturally occurring metal/metalloid having an atomic number greater than 20 and elemental density greater than 5 g/cm^3 is termed as HM. They include copper (Cu), cadmium (Cd), chromium (Cr), cobalt (Co), zinc (Zn), iron (Fe), nickel (Ni), mercury (Hg), lead (Pb), arsenic (As), silver (Ag), and platinum group elements (Ali et al. 2013; Ali and Khan 2018). Among them, Cd, As, Hg, and Pb do not have any biological function in the body and thus are nonessential elements. They can cause severe health hazards and are listed as priority pollutants by many environmental protection agencies worldwide (Jaishankar et al. 2014; Dixit et al. 2015; Sarwar et al. 2017). Therefore, the removal of HMs from the contaminated matrix is an urgent need to safeguard the environment and human health.

Currently, applied physicochemical approaches are environmentally destructive in nature and are also costly to apply. However, bioremediation is considered as the most eco-friendly approach and employs microbes and plants or their enzymes to degrade/detoxify the organic and inorganic pollutants from contaminated environments. Phytoremediation has been identified as an emerging, low-cost, and eco-sustainable solution for HM pollution prevention and control. It is the most suitable alternative to conventional physicochemical remediation technologies, which are highly expensive and technically more suited to small areas, create secondary pollution and deteriorate soil fertility, and, thus, adversely affect agroecosystem (Ali et al. 2013; Chandra et al. 2015; Mahar et al. 2016; Muthusaravanan et al. 2018).

Phytoremediation is the engineered use of green plants with associated soil beneficial microbes to remove toxic pollutants via degradation and detoxification mechanisms from contaminated soil and water/wastewaters (Bharagava et al. 2017; Mukhopadhyay and Maiti 2010; Ali et al. 2013). It is an eco-friendly, nonintrusive, and aesthetically pleasing remediation technology that removes metal pollutants from the contaminated sites (Lee 2013; Chandra et al. 2015; Chirakkara et al. 2016). It can be commercialized, and income can be generated, if metals removed from contaminated sites could be used to extract usable form of economically viable metals (i.e., phytomining) (Chandra et al. 2015; Mahar et al. 2016). In addition, energy can be generated through the burning of plant biomass, and land restoration could be achieved for sustainable agricultural development or general habitation (Stephenson and Black 2014; Mahar et al. 2016). The rationale, mechanisms, and economic feasibility of phytoremediation have been discussed elsewhere (Ali et al. 2013; Wan et al. 2016; Sarwar et al. 2017). However, a longtime frame required for phytoremediation and physiological damage to remediating plants under toxic metal stress is a major issue. Hence, plant–microbe interactions (PMIs) could be exploited to enhance the plant growth and phytoremediation of HM-contaminated sites. Therefore, this chapter has mainly focused on the microbe-assisted phytoremediation, illustrates various mechanisms elicited for plant growth promotion and heavy metal phytoremediation (accumulation/detoxification), and discusses drawbacks and future challenges with recommendations for further research.

6.2 Heavy Metals: Environmental Pollution and Toxicity Profile

Heavy metals (HMs) can be introduced into the environment either by natural or anthropogenic processes. Natural processes are geological activities, for instance, mineral weathering, erosion, volcanic eruptions, and continental dust. Anthropogenic activities include industrial operations such as mining, smelting, electroplating, and industrial effluent discharge as well as agricultural practices like the use of pesticides and phosphate fertilizers and release of agricultural wastes (Ali et al. 2013; Mahar et al. 2016; Antoniadis et al. 2017). Industrial activities are the major source of HM pollution (water and soil) in the environment. If HMs enter the food chain, they may bioaccumulate and/or biomagnify at higher trophic levels resulting in severe health threats and thus are of serious ecotoxicological concern.

The indiscriminate discharge of toxic metal-rich industrial effluents is one of the major sources of environmental pollution. The effluent discharged from metal-based industries, especially leather industries (Cr used in leather tanning), causes serious soil and water pollution, and hence its treatment and management is a key challenge to pollution control authorities (Sahu et al. 2007; Saxena et al. 2016). A high concentration of HMs has been reported in sediments of Ganga River and its tributaries receiving Cr-loaded tannery effluent (Beg and Ali 2008). In addition, HM beyond the permissible limits also deteriorates water quality and makes it unfit for drinking and irrigation purpose (Nazeer et al. 2014). The effluent released from electroplating and distillery industries also constitutes a highly rich source of HMs and hence is considered as hazardous to living beings (Venkateswaran et al. 2007;

Chandra et al. 2008). Furthermore, effluent released from domestic activities is also responsible for HM pollution and thus is of serious ecotoxicological concerns (Bhardwaj et al. 2017).

In an aquatic ecosystem, HM adversely affects gamete production, sperm quality, and embryonic development; delays hatching; causes physical deformities in fishes; and ultimately leads to the death of newly hatched larvae (Segura et al. 2006; Jezierska et al. 2009; Fatima et al. 2014). HM also causes endocrine disruption, oxidative stress, and genotoxicity in fishes (Jezierska et al. 2009; Luszczek-Trojnar et al. 2014; Javed et al. 2016). Further, HM also causes a reduction in hematological parameters and glycogen reserve and thus makes the fishes weak, anemic, and vulnerable to diseases (Javed and Usmani 2015).

The soil is a nonrenewable resource for sustainable agriculture and acts as a major sink for HMs. The contamination of agricultural soil with toxic metals affects its physicochemical and biological properties and reduces land usability for agricultural farming leading to food insecurity and thus creating land tenure problems (Wuana and Okieimen 2011). Moreover, the coexistence and persistence of HMs in soil is also responsible for the entry of toxic metals into the food chain and thus leads to severe health hazards in living beings (Khan et al. 2008).

HM inhibits several microbial metabolic processes such as respiration, denitrification, and enzymatic activity and, hence, retards the bioremediation processes (Zhuang et al. 2007; Sobolev and Begonia 2008). HM also causes a reduction in the number of specific microbial populations and a shift in the microbial community structure. For instance, Ding et al. (2017) evaluated the effect of Cd and Cr on the microbial community structure in the rhizospheric soil of rice plant during a pot experiment. Results revealed that the relative abundance of a bacterial genus *Longilinea* was significantly higher in the control soil than in Cd- and Cr-treated soils, whereas the relative abundance of the genus *Pseudomonas* was significantly higher in the Cd-treated soils than in the Cr-treated and control soils. However, the relative abundance of a genus *Sulfuricurvum* was also significantly higher in the Cd-treated soil than in the Cr-treated and control soils, whereas the relative abundance of the genus *Bellilinea* was significantly higher in the Cr-treated soil than in the other treated soils. HMs also inhibit the cell division, transcription process, and denaturation of protein and adversely affect the cell membrane distribution in microbes (Jacob et al. 2018). Hexavalent chromium (Cr^{6+}) is also reported to cause DNA damage by exerting oxidative stress in soil bacteria and thus leads to genotoxic effects (Quievryn et al. 2003).

The irrigation of food crops in the agriculture field with water contaminated with toxic metal-rich industrial effluents is a common practice in many developing countries. It may provide a chance for the movement of potentially toxic metals from contaminated soil to edible crops, ultimately reaching into the human/animal body via consumption and, thus, rendering severe toxic effects. HM affects various metal-sensitive enzymes in plants such as alcohol dehydrogenase, nitrogenase, nitrate reductase, and amylase and hydrolytic (phosphatase and ribonuclease) and carboxylating (phosphoenolpyruvate carboxylase and ribulose-1,5-bisphosphate carboxylase) enzymes (Nagajyoti et al. 2010; Yadav 2010). Hence, HM disrupts several biochemical/physiological processes in plants such as seed germination, enzymatic activities, nitrogen metabolism, electron transport system, transpiration, CO_2 assimilation, antioxidant defense system, photosynthesis, photophosphorylation, cellular metabolism, nitrogen fixation, water balance, mineral nutrition, and cellular ionic homeostasis and ultimately leads to plant death (Yadav 2010; Lajayar et al. 2017). Irrigation of agricultural crops with heavy metal-loaded industrial effluents also disrupts several cytological processes in plants such as root growth and elongation, cell membrane permeability, mitotic activity, and the stability of genetic material and also creates chromosomal abnormalities (Nagajyoti et al. 2010; Yadav 2010). For example, the irrigation of agricultural crops with the HM-rich distillery and tannery effluent has been reported to cause a reduction in root/shoot growth and biomass, seed germination, and seedling growth and also induce chlorosis and photosynthetic impairment (Chandra et al. 2009).

HMs may cause oxidative stress by forming reactive oxygen species (ROS), which disrupt the antioxidant defense system and lead to cell damage in humans/animals, and in extreme cases can be fatal (Jaishankar et al. 2014). For instance, hexavalent chromium (Cr^{6+}) has been reported to cause cancer in humans and damage cellular components during its reduction into trivalent chromium (Cr^{3+}), leading to the generation of free radicals that cause DNA damage (Mishra and Bharagava 2016). Therefore, the remediation of HM-contaminated sites is of utmost important for environmental safety.

6.3 Current Remediation Technologies: Status and Drawbacks

Rapid industrialization and urbanization around the world has led to the recognition and understanding of the relationship between environmental contamination and public health. Industries are the key players in the national economies of many developing countries; however, unfortunately, they are also the major polluters of the environment. Among the different sources of environmental pollution, industrial wastewater discharged from different industries is considered the major source of environmental pollution (soil and water). Industries use a variety of chemicals for the processing of raw materials to obtain good-quality products within a short period of time and economically. To obtain good-quality products within a short period of time, industries generally use cheap and poorly or nonbiodegradable chemicals, and their toxicity is usually ignored. However, in the public domain, there are many reports available that confirm the presence of a variety of highly toxic chemicals in industrial wastewaters.

Industrial wastewaters contain a variety of organic and inorganic pollutants that cause serious environmental pollution and health hazards (Maszenan et al. 2011; Megharaj et al. 2011). During production processes, a variety of chemicals with large volumes of water are used to process raw materials in industries. This generates large volumes of high-strength wastewater, which is a major source of environmental pollution (Saxena et al. 2016). The wastewater generated from pollution-causing industries is characterized by high chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDSs), total suspended solids (TSSs), and a variety of recalcitrant organic and inorganic pollutants. Organic pollutants include phenols, chlorinated phenols, endocrine-disrupting chemicals, azo dyes, polyaromatic hydrocarbons, polychlorinated biphenyls, and pesticides, whereas inorganic pollutants include a variety of toxic heavy metals such as cadmium (Cd), chromium (Cr), arsenic (As), lead (Pb), and mercury (Hg). The high concentration and poor biodegradability of recalcitrant organic pollutants and nonbiodegradable nature of inorganic metal pollutants in industrial wastewaters pose a major challenge for environmental safety and human health protection; thus, it is required to adequately treat industrial wastewater before its final disposal in the environment. Although a number of physicochemical methods are applied for the treatment of industrial wastewaters, all of these are costly, use a large amount of chemicals, and generate a large amount of sludge after treatment, which also acts as a secondary pollutant in the environment. Alternatively, biological treatment methods using an array of microorganisms have diverse metabolic pathways and, hence, are regarded as environmentally friendly, cost-effective methods for wastewater treatment with simple structural setup, wider application, operational ease, and less sludge production compared to physicochemical methods (Mendez-Paz et al. 2005; Pandey et al. 2007). Biological methods using microbes are becoming much more popular for the treatment of industrial wastewaters in wastewater treatment plants. Further, most chemical compounds are degraded by acclimated microorganisms during wastewater treatment at wastewater treatment plants; however, some of the chemical compounds are not properly degraded/detoxified due to their recalcitrant nature during wastewater treatment and are discharged along with wastewaters, causing serious environmental pollution (Maszenan et al. 2011). Hence, the application of bioremediation technology using potential microorganisms and their consortia or of phytoremediation technology (use of green plants in constructed wetlands) is required for the degradation and detoxification of such types of recalcitrant industrial wastewaters prior to safe disposal in the environment.

Phytoremediation is considered as the most applicable remediation technology at contaminated sites. Phytoremediation is the engineered use of green plants with associated soil beneficial microbes to remove toxic pollutants via degradation and detoxification mechanisms from contaminated soil and water/wastewaters (Bharagava et al. 2017; Mukhopadhyay and Maiti 2010; Ali et al. 2013). It is an eco-friendly, nonintrusive, and aesthetically pleasing remediation technology that removes metal pollutants from the contaminated sites (Lee 2013; Chandra et al. 2015; Chirakkara et al. 2016). The aim of phytoremediation can be (a) plant-based extraction of metals with financial benefit (phytoextraction), (b) risk minimization (phytostabilization), and (c) sustainable soil management in which phytoremediation steadily increases soil fertility allowing growth of crops with added economic value (Mahar et al. 2016; Vangronsveld et al. 2009). Phytoremediation includes a range of plant-based remediation processes. Phytoremediation reduces the risks of pollutant dispersion, and it is applicable for the decontamination of soils or wastewaters with mixed pollutants (Mahar et al. 2016; Mudhoo et al. 2010). Mechanisms and efficiency of phytoremediation depend on several factors such as the pollutant class, its bioavailability especially in soils, physical and chemical characteristics of the matrix (soil, water, and wastewaters), and plant species (Mahar et al. 2016; Sreelal and Jayanthi 2017). The plants considered more efficient for phytoremediation are the metallophytes. These are able to survive and reproduce on metal-polluted soils (Coninx et al. 2017; Alford et al. 2010). However, a great number of known metallophytes have small biomass and slow growth, characteristics that are not advantageous for phytoremediation technologies (Coninx et al. 2017; Cabral et al. 2015). Further, longtime frame required for phytoremediation and physiological damage to remediating plants under toxic metal stress is a major issue. Therefore, plant–microbe interactions (PMIs) could be exploited to enhance the plant growth and phytoremediation of HM-contaminated sites.

The root-/rhizosphere-colonizing, plant growth-promoting rhizobacteria (PGPR) have been reported to enhance host plant growth in toxic metal-contaminated sites (Yuan et al. 2013; Ma et al. 2015, 2016a). PGPR produces growth hormones such as auxins (IAA, indole-3-acetic acid), cytokinins, gibberellins, and ethylene (Rajkumar et al. 2012; Ma et al. 2015). The mechanisms of plant growth promotion may vary from bacterial strain to strain and depend on various secondary metabolites produced (Ma et al. 2011; Backer et al. 2018). PGPR also produces some other beneficial compounds such as enzymes, osmolytes, biosurfactants, organic acids, metal-chelating siderophores, nitric oxide, and antibiotics (Rajkumar et al. 2012; Ma et al. 2015). These beneficial compounds reduce ethylene production *via* synthesis of ACC (1-aminocyclopropane-1-carboxylate) deaminase that prevents the inhibition of root elongation, lateral root growth, and root hair formation and also improves the mineral (N, P, & K) uptake in acidic soil (Babu et al. 2013; Ma et al. 2015). These compounds also suppress phytopathogens, provide tolerance to abiotic stress, and help in associated nitrogen fixation (Rajkumar et al. 2012; Babu et al. 2013; Ma et al. 2015). Hence, PGPRs are applied in sustainable agriculture development. Besides these, PGPR can lower the metal toxicity to remediating plants through biosorption/bioaccumulation as bacterial cells have an extremely high ratio of surface area to volume (Ma et al. 2016b; Li et al. 2018). PGPR could adsorb high metal concentration by either a metabolism-independent passive or metabolism-dependent active processes. Hence, using PGPR in environmental bioremediation could be a useful strategy for plant survival in the stressed environment. PGPRs reported for the enhanced HM phytoremediation with associated benefits have been reviewed in the past (Ma et al. 2011; Rajkumar et al. 2012; Ullah et al. 2015). Some updated examples from recent studies are summarized in Table 6.1.

Endophytes are the microbes (bacteria/fungi) that reside in the inner tissues of plants without causing harm to host. They also help in plant growth promotion and development under biotic or abiotic stressed environment and exert many beneficial effects than rhizobacteria (Luo et al. 2011; Ma et al. 2011, 2015). They are able to tolerate high metal concentration and hence lower phytotoxicity to remediating plants as well as help in growth promotion enhancing through biocontrol mechanism and induced systemic resistance against phytopathogens (Ma et al. 2011, 2015). They produce phytohormones, organic acids, siderophores, biosurfactants,

Table 6.1 Some studies on microbe-assisted phytoremediation of heavy metal-contaminated soils

Bacterial strain(s)	Host plant	Heavy metal	Medium	Beneficial effects	References
Plant growth-promoting rhizobacteria (PGPR)					
Enterobacter sp. LC1, LC4, & LC6; *Kocuria* sp. LC2 & LC5; and *Kosakonia* sp. LC7	*Solanum nigrum*	As	Soil	IAA and P-solubilization	Mukherjee et al. (2018)
Pseudomonas libanensis and *Pseudomonas reactans*	*Brassica oxyrrhina*	Cu, Zn	Soil	IAA, ACC deaminase, siderophores	Ma et al. (2016a)
Pseudomonas putida, *Rhodopseudomonas* sp.	*Cicuta virosa L.*	Zn	Soil	Metal-chelating compounds	Nagata et al. (2015)
Rhizobium leguminosarum	*Brassica juncea*	Zn	Soil	Metal chelation	Adediran et al. (2015)
Photobacterium spp.	*Phragmites australis*	Hg	Soil	IAA, mercury reductase activity	Mathew et al. (2015)
Bacillus pumilus E2S2 and *Bacillus* sp. E1S2	*Sedum plumbizincicola*	Cd	Soil	IAA, ACC deaminase, siderophores, P-solubilization	Ma et al. (2015)
Pseudomonas sp. LK9	*Solanum nigrum*	Cd	Soil	Biosurfactants, siderophores, organic acids	Chen et al. (2014)
P. aeruginosa	*Triticum aestivum*	Zn	Soil	Antioxidative enzymes (catalase, peroxidase, superoxide dismutase)	Islam et al. (2014)
Mesorhizobium Amorphae	*Robinia pseudoacacia*	Cu, Zn, Cr	Soil	IAA, induced stress Tolerance	Hao et al. (2013)
Acinetobacter sp.	*Cicer arietinum*	As	Soil	IAA production	Srivastava and Singh (2014)
Enterobacter sp. JYX7 and *Klebsiella* sp. JYX10	*Polygonum pubescens*	Cd	Soil	IAA, siderophores, ACC deaminase, P-solubilization	Jing et al. (2014)
Bacillus subtilis, *Bacillus cereus*, *B. megaterium*	*Orychophragmus violaceus*	Cd	Soil	IAA production	Liang et al. (2014)

(continued)

Table 6.1 (continued)

Bacterial strain(s)	Host plant	Heavy metal	Medium	Beneficial effects	References
Plant growth-promoting rhizobacteria (PGPR)					
Phyllobacterium myrsinacearum RC6b	*Sedum plumbizincicola*	Cd, Zn, and Pb	Soil	ACC deaminase, IAA, siderophores, P solubilization	Ma et al. (2013)
Staphylococcus arlettae NBRIEA G-6	*B. juncea*	As	Soil	IAA, siderophores, ACC deaminase	Srivastava et al. (2013)
Rahnella sp.	*Amaranthus hypochondriacu*, *A. mangostanus*, and *S. nigrum*	Cd	Soil	IAA, siderophores, ACC deaminase, P-solubilization	Yuan et al. (2013)
Paenibacillus macerans NBRFT5, *Bacillus endophyticus* NBRFT4, and *Bacillus pumilus* NBRFT9	*Brassica juncea*	Ni	Mix. of fly ash and press mud	Siderophores, organic acids, protons, and other nonspecified enzymes	Tiwari et al. (2012)
Pantoea agglomerans Jp3-3 and *Pseudomonas thivervalensis* Y1-3-9	*Brassica napus*	Cu	Quartz sand	IAA, siderophores, ACC deaminase, P-solubilization	Zhang et al. (2011)
Azotobacter chroococcum and *Rhizobium leguminosarum*	*Zea mays L.*	Pb	Soil	IAA production increased and soil pH decreased	Hadi and Bano (2010)
Bacillus subtilis, *B. cereus*, *Flavobacterium* sp., and *Pseudomonas* sp.	*Orychophragmus violaceus*	Zn	Soil	ACC deaminase, IAA, siderophores	He et al. (2010)
Achromobacter xylosoxidans Ax10	*Brassica juncea*	Cu	Soil	ACC deaminase, IAA, phosphate solubilization	Ma et al. (2009)
Burkholderia sp. J62	*Zea mays and Lycopersicon Esculentum*	Pb, Cd	Soil	IAA, siderophores, ACC deaminase, P solubilization	Jiang et al. (2008)
Burkholderia sp. J62	*B. juncea*	Zn, Pb, Cu	Soil	P, K solubilization	Wu et al. (2006)
Brevibacillus brevis	*Trifolium repens*	Cd, Ni, Pb	Soil	IAA production	Vivas et al. (2006)
Endophytes					

(continued)

Table 6.1 (continued)

Plant growth-promoting rhizobacteria (PGPR)					
Bacterial strain(s)	Host plant	Heavy metal	Medium	Beneficial effects	References
Bacillus thuringiensis GDB-1	*Alnus firma*	As	Mine tailing waste	ACC deaminase, IAA, siderophores, P-solubilization	Babu et al. (2013)
Pseudomonas koreensis AGB-1	*Miscanthus Sinensis*	As, Cd, Cu, Pb, and Zn	Soil	ACC deaminase activity, IAA	Babu et al. (2015)
Staphylococcus, *Curtobacterium*, *Bacillus*, *Pseudomonas*, *Microbacterium*, *Arthrobacter*, *Leifsonia*, *Paenibacillus*	*Alyssum bertolonii*	Ni, Co, Cr, Cu, and Zn	Soil	Production of siderophores	Barzanti et al. (2007)
Serratia nematodiphila LRE07, *Enterobacter aerogenes* LRE17, *Enterobacter* sp. LSE04 *Acinetobacter* sp. LSE06	*Solanum nigrum* L.	Cd	Soil	Production of IAA, siderophores, ACCD, and solubilization of P	Chen et al. (2010)
P. monteilii PsF84, *P. plecoglossicida* PsF610	*Pelargonium graveolens*	Cr	Soil	Production of IAA and siderophores, solubilization of P	Dharni et al. (2014)
Rahnella sp. JN6	*Brassica napus*	Pb	Soil	IAA, ACC deaminase, siderophores, P-solubilization	He et al. (2014)
Actinobacterium	*Salix caprea*	Cd and Zn	Soil	Production of siderophores and ACCD	Kuffner et al. (2010)
Burkholderia cepacia L.S.2.4, *Herbaspirillum seropedicae* LMG2284	*Lupinus luteus* L	Cu, Cd, Co, Ni, Pb, and Zn	Soil	ND	Lodewyckx et al. (2001)

(continued)

Table 6.1 (continued)

Plant growth-promoting rhizobacteria (PGPR)					
Bacterial strain(s)	Host plant	Heavy metal	Medium	Beneficial effects	References
Pseudomonas fluorescens VI8L1, *Bacillus pumilus* VI8L2, *P. fluorescens* II8L4, *P. fluorescens* VI8R2, *Acinetobacter calcoaceticus* II2R3	*Sedum alfredii*	Zn and Cd	Soil	Production of IAA, siderophores, fixation of nitrogen, solubilization of ZnCO3 and Zn3(PO4)2	Long et al. (2011)
Serratia marcescens LKR01, *Arthrobacter* sp. LKS02, *Flavobacterium* sp. LKS03, *Chryseobacterium* sp. LKS04	*Solanum nigrum* L.	Zn, Cd, Pb, and Cu	Soil	Production of IAA, siderophores, ACCD, and solubilization of P	Luo et al. (2011)
Serratia sp. LRE07	*S. nigrum* L	Cd, Cr, Pb, Cu, and Zn	Soil	Production of IAA, siderophores, and solubilization of P	Luo et al. (2011)
Bacillus sp. SLS18	*Sorghum bicolor* L.	Cd and Mn	Soil	Production of IAA, siderophores, and ACCD	Luo et al. (2011)
Pseudomonas sp. A3R3	*Alyssum serpyllifolium*	Ni	Soil	Production of IAA, siderophores, ACCD, and solubilization of P; excreted cellulase and pectinase	Ma et al. (2011)
Methylobacterium oryzae CBMB20, *Burkholderia* sp. CBMB40	*Lycopersicon esculentum*	Ni and Cd	Soil	ND	Madhaiyan et al. (2007)
P. fluorescens G10, *Microbacterium* G16	*Brassica napus*	Pb, Cd, Zn, Cu, and Ni	Soil	Production of IAA, siderophores, ACCD	Sheng et al. (2008)

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Table 6.1 (continued)

Bacterial strain(s)	Host plant	Heavy metal	Medium	Beneficial effects	References
Plant growth-promoting rhizobacteria (PGPR)					
Bacillus sp. MN3-4	*Alnus firma* and *B. napus*	Pb, Cd, Zn, Ni, and Cu	Soil	Production of IAA and siderophores	Shin et al. (2012)
Endophytes belonged to *Firmicutes*, *Actinobacteria*, Proteobacteria	*Elsholtzia splendens*, *Commelina communis*	Cu	Soil	Production of IAA, siderophores, ACCD, and arginine decarboxylase	Sun et al. (2010)
Microbacterium sp. NCr-8, *Arthrobacter* sp. NCr-1, *Bacillus* sp. NCr-5, *Bacillus* sp. NCr-9, and *Kocuria* sp. NCr-3	*Noccaea caerulescens*, *Thlaspi perfoliatum*	Ni	Soil	Production of IAA, siderophores, and ACCD	Visioli et al. (2014)
Serratia nematodiphila LRE07	*Solanum nigrum* L.	Cd	Soil	ND	Wan et al. (2012)
Rahnella sp. JN27	*Amaranthus hypochondriacus* and *A. mangostanus*	Cd	Soil	Production of IAA, siderophores, ACCD, and solubilization of P	Yuan et al. (2014)
Burkholderia sp. SaZR4, *Burkholderia* sp. SaMR10, *Sphingomonas* sp. SaMR12, and *Variovorax* sp. SaNR1	*Sedum alfredii* Hance	Cd and Zn	Soil	ND	Zhang et al. (2013)
Endophytes belonged to *Firmicutes*, *Proteobacteria*, and *Actinobacteria*	*Pteris vittata* and *P. multifida*	As	Soil	Production of IAA	Zhu et al. (2014)
Arbuscular mycorrhizal fungi					

(continued)

Table 6.1 (continued)

Plant growth-promoting rhizobacteria (PGPR)					
Bacterial strain(s)	Host plant	Heavy metal	Medium	Beneficial effects	References
Glomus mosseae	*Trifolium subterraneum*, *Lolium perenne*	Cd, Zn	Soil	AMF adsorbed up to 0.5 mg Cd per gram of mycelia equivalent to threefold binding capacity of non-tolerant fungi or tenfold higher than reported for *Rhizopus arrhizus* (commonly used as biosorption organism)	Joner et al. (2000)
Glomus intraradices	*Helianthus annuus*	Cr	Soil	AMF increased fivefold root Cr concentration	Davies et al. (2001)
Glomus mosseae, *Glomus caledonium*, and *Glomus claroideum*	*Sorghum vulgare*	Cu	Soil	RM increased Cu-sorption from 2.3 to 13.8 mg Cu g^{-1} dry mycelium	
Glomus mosseae	*Trifolium pratense* L	Zn	Soil	22% of total Zn plant uptake linked to ERM	Chen et al. (2003)
Gigaspora rosea and *Glomus mosseae*	*Zea mays* and *Sorghum vulgare*	Cu	Soil	GRSP produced by *G. rosea* hyphae bound up to 28 mg Cu g^{-1} and *G. mosseae* ranged from 1.0 to 1.6 mg Cu g^{-1}	Gonzalez-Chavez et al. (2004)
Mixed spores of mycorrhizal fungal species isolated from orchard soil	*Kummerowia striata*, *Ixeris denticulata*, *Lolium perenne*, *Trifolium repens*, and *Echinochloa crus-galli*	Pb	Soil	AMF inoculation increased the Pb root concentration from 7.6% to 57.2%	Chen et al. (2005)
Indigenous mycorrhizal populations from polluted soils	*Argemone subfusiformis*, *Baccharis linearis*, *Oenothera affinis*, *Polypogon viridis*	Cu, Zn	Soil	GRSP bound from 1.4% to 28% of total Cu in soil and from 1.4% to 5.8% of total Zn	Cornejo et al. (2008)

(continued)

Table 6.1 (continued)

Plant growth-promoting rhizobacteria (PGPR)					
Bacterial strain(s)	Host plant	Heavy metal	Medium	Beneficial effects	References
Indigenous mycorrhizal populations from polluted soils	Degraded ecosystem with presence of *Sesleria caerulea*	Pb, Zn	Soil	GRSP bound Pb attained until 23.4 mg g^{-1}, which represents about 16% of total soil Pb	Vodnik et al. (2008)

enzymes, and growth regulators that help in water and nutrient (P, N, & K) uptake, osmolyte accumulation, osmotic adjustment, stomatal regulation, and associated nitrogen fixation as additional benefits to host plants (Ma et al. 2011, 2016b). Thus, inoculating plants with endophytes could be an excellent strategy to enhance the phytoremediation of HM-contaminated sites. Endophytes applied to enhance HM phytoremediation with associated benefits have been recently reviewed by several researchers (Afzal et al. 2014; Ma et al. 2016b).

Arbuscular mycorrhizal fungi (AMF: colonize plant roots) have been also reported to protect their host plants against heavy metal toxicity through their mobilization from soil and thus help in phytoremediation (Marques et al. 2009; Meier et al. 2012; Khan et al. 2014). The possible mechanisms by which AMF protect their host plants through metal mobilization from soil include:

(a) Immobilization by chelation;
(b) Binding of metals to biopolymers in the cell wall;
(c) Superficial immobilization in the plasmatic membrane once metals cross the cell wall;
(d) Membrane transportation that mobilizes metals from the soil to the cytosol;
(e) Intracellular chelation through MTs, organic acids, and amino acids;
(f) Export of metals from cytosol by membrane transporters;
(g) Sequestration of metals into vacuoles;
(h) Transportation of metals by means of fungal hyphae;
(i) Storage of metals in fungal spores; and
(j) Exportation by the fungus and access into the plant cells, involving both active and passive transportation into the mycorrhizae (Meier et al. 2012; Cabral et al. 2015).

They confer resistance against drought, high salt, and toxic metal concentration and improve nutrient supply and soil physical properties (Khan et al. 2014). The exact mechanism of plant protection is still not fully understood, and further research is required to explore their role in the phytoremediation.

6.4 Microbe-Assisted Phytoremediation: Concepts and Mechanisms

Most plants growing in polluted environments are often characterized by relatively low growth caused by toxic effects of accumulated substances or their degradation products (Glick 2003). However, the negative effect of the environment can be alleviated by soil microorganisms. The soil is an environment settled by a wide range of genetically diverse microorganisms, which play crucial roles in nutrient cycling and in soil-forming processes (Ahemad and Khan 2013). They include both bacteria, which are the most numerous (9×10^7 in one gram of typical soil), and fungi (2×10^5) (Alexander 1991). Microorganisms inhabiting metalliferous soils often exhibit tolerance to high concentrations of heavy metals (HMs) in the environment. Many studies have confirmed that interactions between plants and metallo-tolerant microorganisms facilitate the recultivation of HM-polluted areas (e.g., Chen et al. 2014; Ma et al. 2015; Złoch et al. 2017). This synergism can accelerate the process of remediation by phytostabilization or phytoextraction of HMs but can also increase plant growth and development under adverse environmental conditions (Khan et al. 2009). The functioning of plant–microorganism associations in HM-contaminated soils depends on both the microorganisms and the plant host (Egamberdieva et al. 2016). The plant roots secrete exudates that are the source of nutrients for microorganisms and also increase the solubility of macro- and microelements affecting the activity of microorganisms associated with plant roots (Iqbal and Ahemad 2015). Plant-associated microorganisms can play significant roles in nutrient cycling, improving soil structure, detoxifying harmful contaminants, modulating plant defense responses to stress factors, and assisting in biological control of phytopathogens and plant growth (Elsgaard et al. 2001; Filip 2002; Giller et al. 1998).

To generalize, the activity of microorganisms inhabiting the roots (endophytes) or rhizosphere can increase the capacity of metalliferous soil phytoremediation as follows:

1. Directly: Plant-associated microorganisms directly increase the uptake and translocation of metals (facilitation of phytoextraction) or reduce the mobility/availability of metals within the rhizosphere (phytostabilization).
2. Indirectly: Microorganisms increase plant tolerance to HMs and/or promote plant biomass production in order to remove/stabilize contaminants. A general outline of plant–microbe–metal interactions for the phytoremediation of heavy metal-contaminated soils is shown in Fig. 6.1.

6.4.1 Direct Mechanisms

In most metalliferous soils, HMs are strongly adsorbed onto soil particles and are therefore hardly available for plant roots during phytoextraction (Gamalero and Glick 2012). Microorganisms can increase their solubility and availability via (a) auto- and heterotrophic leaching (associated with redox reaction), (b) secretion of

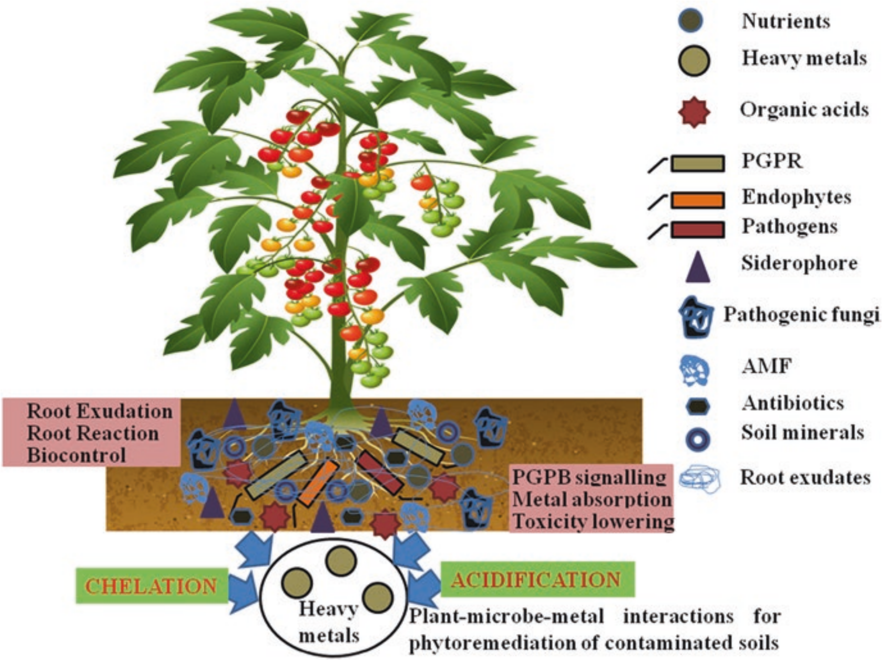

Fig. 6.1 Outline mechanism of plant–microbe–metal interactions for microbe phytoremediation of heavy metal-contaminated sites

organic acids and biosurfactants, and (c) release of siderophores (Gadd 2004; Wenzel 2008; Li et al. 2012). These processes can lead to the dissolution of minimally soluble metal–mineral compounds (including phosphates, sulfates, and more complex ores) as well as metal desorption from the surface of clay minerals or organic matter (Gadd 2004). Microorganisms can acidify the environment by releasing H+ through the transmembrane H^+-ATPase, maintaining the membrane potential or as a result of carbon dioxide accumulation generated during respiratory processes, which leads to the release of free metal cations from their complexes with anions *via* ion exchange occurring between H^+ and metals (Gadd 2004). In most cases, autotrophic leaching of metals is performed by acidophilic bacteria, which assimilate carbon dioxide and produce energy from Fe^{2+} oxidation or sulfur compound reduction (Rawlings 1997; Schippers and Sand 1999). Moreover, many studies have confirmed that rhizosphere bacteria such as *Thiobacillus thiooxidans* are interesting in the context of phytoextraction because they reduce rhizosphere pH through the conversion of reduced sulfur into sulfate, improving the availability of Cu, for example, to plants (Rawlings and Silver 1995; Shi et al. 2011). In recent years, much attention has been paid to the phenomenon of low-molecular-weight organic acids (LMWOAs, compounds with molecular weights ≤300 Da and containing one or more carboxylic groups) being secreted by plant-associated microorganisms and their potential role in the regulation of HM solubility and mobilization of mineral compounds within the rhizosphere (Rajkumar et al. 2012).

Chelators are mainly known to enhance the solubility of HMs and include citric, lactic, malic, oxalic, malonic, 5-ketogluconic, tartaric, succinic, and formic acids (Panhwar et al. 2013). Commonly synthesized oxalates and citrates are known for their ability to form stable complexes with many HMs; furthermore, citrates are highly mobile and highly resistant to degradation (Francis et al. 1992). Saravanan et al. (2007) observed that during secretion of 5-ketogluconic acid by an endophytic bacterium of *Gluconacetobacter diazotrophicus*, various Zn^{2+} sources (e.g., ZnO, $ZnCO_3$, or $Zn_3(PO_4)_2$) are dissolved, which increases the pool of Zn^{2+} readily available for roots. Moreover, Han et al. (2006) revealed stimulatory effects of acetic and malic acid on the Cd^{2+} accumulation in the roots of corn (*Zea mays* L.). Similar observations were noticed in the case of, for example, increased uptake of Cd^{2+} and Zn^{2+} by *Sedum alfredii* due to secretion of formic, acetic, tartaric, succinic, and oxalic acids by rhizosphere bacteria (Li et al. 2010) as well as stimulation of Cd^{2+} uptake by wheat in the presence of citric acid (Panfili et al. 2009). Regarding synthesis of LMWOAs, particularly oxalate, by fungal strains, it has also been suggested that the release of metal ions *via* enhanced mineral weathering plays an important role and leads to the uptake of HMs by plants and microorganisms (Jones 1998; Gadd and Sayer 2000). Such an ability was noted for *Beauveria caledonica*, *Aspergillus niger*, *Penicillium bilaiae*, or *Oidiodendron maius* in the case of cadmium, copper, lead, nickel, or zinc mineral solubilization (Martino et al. 2003; Fomina et al. 2005; Arwidsson et al. 2010). Another important class of metabolites with great potential to increase metal mobility and stimulate the phytoremediation process is the microbial surface-active substances called biosurfactants (Rajkumar et al. 2012). Biosurfactants are amphiphilic molecules consisting of long nonpolar parts (hydrophobic) and polar/ionic (hydrophilic) heads. Their hydrophilic parts consist of mono-, oligo-, or polysaccharides, peptides, and proteins, while their hydrophobic parts usually contain saturated, unsaturated, and hydroxylated fatty acids or fatty alcohols. Siderophores are low-molecular-weight organic compounds (500–1500 Da) with high specificity and affinity for Fe^{3+} chelation (Miethke and Marahiel 2007), which release iron from minerals or organic matter in order to facilitate iron uptake when its availability in the environment is limited (Li et al. 2012). Despite the substantial diversity of chemical structures of siderophores (over 500 diverse siderophores described to date), they can be divided into several groups depending on the presence of metal-binding ligands: (a) hydroxamates, (b) catecholates, (c) phenolates, (d) carboxylates, and (e) mixed (Essen et al. 2006; Saha et al. 2013; Wang et al. 2014; Pluhacek et al. 2016). While the key role of siderophores in iron homeostasis in microorganisms has been well known for over 60 years, there is increasing evidence for the activation of siderophore synthesis by bacteria in the presence of toxic metals, which indicates their potential role in HM homeostasis (Schalk et al. 2011; Złoch et al. 2016). It was suggested that siderophores may form stable complexes with ions such as Ag^{+}, Zn^{2+}, Cu^{2+}, Co^{2+}, Cr^{2+}, Mn^{2+}, Cd^{2+}, Pb^{2+}, Ni^{2+}, Hg^{2+}, Sn^{2+}, Al^{3+}, In^{3+}, Eu^{3+}, Ga^{3+}, Tb^{3+}, and Tl^{+}. Enhanced siderophore synthesis by bacteria (so-called siderophore-producing bacteria, SPB) can protect them from the toxic effects of HMs by, for example, extracellular sequestration, thereby preventing metals from entering into the cells (Saha et al. 2013). Similar observations were noted for fungi; however, the relatively weak ability of fungal siderophores (mainly hexadentate hydroxamate) to chelate HMs other than Fe(III) (Enyedy et al. 2004; Farkas et al. 2008) makes their potential in HM bioremediation rather limited (Pocsi 2011). On the other hand, increased siderophore synthesis can improve the phytoextraction capacity of plants by increasing the mobility of metals and thus their availability for roots (Glick 2003; Rajkumar et al. 2010).

6.4.2 Indirect Mechanisms

The most important mechanisms, and those confirmed so far in the scientific literature, are (a) the synthesis of phytohormones and enzymes (primarily indole-3-acetic acid [IAA], 1-aminocyclopropane-1-carboxylate [ACC] deaminase), (b) increased nutrient uptake (nitrogen fixation, phosphorus, and iron mobilization), and (c) tolerance to biotic (pathogen control) and abiotic (drought, salinity, contamination) stress conditions (Hrynkiewicz and Baum 2012; Ma et al. 2016b). The specific response of nitrogen-fixing legumes in response to Cd, like an overproduction of reactive oxygen species (ROS) in the nodules and its mitigation by PGPB (e.g., by the release of siderophores), was reviewed by Gomez-Sagasti and Marino (2015). IAA is one of the most important phytohormones and regulates many physiological and morphological functions of plants (Glick 2012). In addition to stimulation of root growth, alleviating salt stress, participating in plant–pathogen interactions, and eliciting induced systemic resistance (ISR) against various diseases, IAA is primarily involved in stimulating the proliferation of lateral roots. IAA-synthesizing microorganisms can indirectly increase the extraction of metals and nutrient supplementation of plants by inducing root proliferation and increasing their uptake surface (Glick 2010). Apart from IAA, soil microorganisms demonstrate the ability to synthesize other phytohormones (cytokinins, gibberellins). However, fungi are also known for their ability to secrete compounds similar to phytohormones such as auxins, cytokinins, gibberellic acids, or ethylene (Chanclud and Morel 2016). Ethylene is a crucial phytohormone that regulates plant cell elongation and metabolism (Ping and Boland 2004), and its overproduction induced by stress factors, such as HMs, may inhibit processes involved in plant development (i.e., root elongation, lateral root growth, and formation of root hairs) (Mayak et al. 2004). Microbial ACC deaminase causes the hydrolysis of 1-aminocyclopropane-1-carboxylic acid (an ethylene precursor) to α-ketobutyric acid and ammonia, which can be used as a source of carbon and nitrogen by microorganisms. Thus, inoculation of plants with strains synthesizing ACC deaminase indirectly affects root growth and proliferation and positively influences the plant biomass and efficiency of HM phytoremediation (Gleba et al. 1999; Agostini et al. 2003; Arshad et al. 2007). ACC deaminase-containing bacteria are relatively common in soil (typically free-living pseudomonads) (Glick 2005, 2014), while among fungi, this activity is less frequently observed (although it has been reported in *Penicillium* *citrinum* and *Trichoderma asperellum* T203) (Jia et al. 2000; Viterbo et al. 2010) and has not been investigated in detail. The presence of elevated amounts of HMs often affects the supplementation of plant roots with Fe, P, Mg, or Ca, leading to plant growth retardation (Ouzounidou et al. 2006; Parida et al. 2003). Under such conditions, plant-associated microorganisms facilitate the uptake of nutrients by increasing their availability for plant roots (Rajkumar et al. 2012). Examples include the bacteria reported by Nautiyal et al. (2000), which demonstrate the ability to increase P availability for plants through phosphate precipitation by acidification of the soil solution, complexation, secretion of organic acids, and ion-exchange reactions or through mineralization of organic phosphorus compounds secreting acid phosphatase (van der Hiejden et al. 2008). Among P-solubilizing microorganisms, fungal strains belonging to *Aspergillus* and *Penicillium* are known for their strong ability to release P from insoluble inorganic compounds, primarily by producing organic acids and preventing the precipitation of P with metals (Jones 1998; Mendes et al. 2014). A similar effect is observed for iron, which is present in the Earth's crust in large quantities; however, iron is found mostly as insoluble hydroxides and oxyhydroxides that are not readily available to plants (Budzikiewicz 2010; Rajkumar et al. 2010). Moreover, plants growing in metalliferous soils are very often exposed to iron deficiency, which produces a decreased photosynthesis rate and consequently a decline in their growth and development (Nagajyoti et al. 2010a, b). In such cases, inoculation of plants with SPB can be a promising method to mitigate iron deficiency (Iqbal and Ahemad 2015). Many studies have confirmed that SPB successfully increased chlorophyll concentration and improved other plant growth parameters in the presence of HM contamination in the soils by facilitating iron uptake (Burd et al. 1998, 2000, Carrillo-Castaneda et al. 2003, Barzanti et al. 2007). It has also been observed that the synthesis of siderophores may stimulate plant growth in metalliferous areas via the following activities: (a) involvement in maintaining an appropriate level of IAA through binding of HMs, thereby reducing the inhibitory effect of metals on the IAA biosynthesis pathways, and through decreased production of reactive oxygen species (ROS), which can degrade IAA molecules; (b) mitigation of oxidative stress by stimulation of peroxidase activity; and (c) phytopathogen control via chelation of iron ions within the rhizosphere and decreasing the availability of iron for pathogens (Dimkpa et al. 2008; Rajkumar et al. 2009).

6.5 Microbe-Assisted Phytoremediation of Heavy Metal-Contaminated Sites

It has been well demonstrated that the inherent ability of endophytic bacteria may help host plants adapt to unfavorable soil conditions and enhance the efficiency of phytoremediation by promoting plant growth, alleviating metal stress, reducing metal phytotoxicity, and altering metal bioavailability in soil and metal translocation in plant (Ma et al. 2011; Ozyigit and Dogan 2015). Overall, the plant-associated microbes promote phytoremediation process in metal-polluted soils by two distinct means, i.e., enhancement of plant metal tolerance and growth and alteration of metal accumulation in plants, as discussed in above sections. Some important studies on the phytoremediation of heavy metal-contaminated soils assisted by plant growth-promoting rhizobacteria, endophytes, and arbuscular mycorrhizal fungi have been summarized in Table 6.1.

6.6 Challenges and Future Perspectives

The success of phytoextraction depends on interactions among soil, metals, and plants. Many plants are not capable of gaining sufficient biomass for noticeable rates of remediation when elevated levels of pollutants are present (Harvey et al. 2002; Chaudhry et al. 2005). The remediation process of contaminated soils is limited and slowed because of their poor nutrient nature. Soil microbes are thought to exert positive effects on plant health via mutualistic relationships between them. However, microbes are sensitive to pollution, and depletion of microbial populations, both in terms of diversity and biomass, often occurs in such contaminated soils (Shi et al. 2002). Biotic or abiotic stress through a small change in the physicochemical–biological properties of rhizosphere soils can cause a dramatic effect on plant–microbe interaction. Further, isolation and characterization of suitable plant-associated beneficial microbes is a time-consuming process. It also requires the analysis of more than thousands of isolates, and thus identification of specific biomarkers may help to select the effective plant–microbe interactions for microbe-assisted phytoremediation (Rajkumar et al. 2012). Further, to ameliorate metal toxicity, plant growth promotion, and metal sequestration, extensive research efforts are also required to explore novel microbial diversity, their distribution, and functions in the autochthonous and allochthonous soil habitats for microbe-assisted phytoremediation of HM-contaminated sites.

6.7 Conclusions and Recommendations

(a) HM pollution in the environment and associated toxicity in living beings is of serious eco-environmental concern.
(b) Inoculation of plants with associated microbes (such as PGPRs, endophytes, and arbuscular mycorrhizal fungi) exhibiting multiple traits could be an excellent strategy to enhance metal detoxification in the rhizosphere. A clear-cut understanding of plant–microbe–metal–soil interactions is crucial for microbe-assisted phytoremediation of HM-contaminated soils.
(c) The effectiveness of co-inoculation of PGPB and AMF in response to multiple biotic and/or abiotic stresses must be assessed for better applicability at field.
(d) Identification of functional genes of beneficial microbes responsible for growth enhancement and metal detoxification should be identified.

(e) Trials for the commercial production of bioinoculants for use in metal decontamination should be performed to make a positive remark toward their field applicability.
(f) Genetic engineering of metal-accumulating plants and associated microbes with required traits could be a very useful strategy for the enhanced phytoremediation, but associated risks should also be considered before field application.
(g) A detailed and accurate characterization of target metal(loid)-contaminated soils is needed before the inoculation of microbes, as well as adequate strategies to enhance inoculant performance by using efficient carrier materials.
(h) The complexity and heterogeneity of soils contaminated with multiple metals and organic compounds requires the design of integrated phytoremediation systems that combine different processes and approaches.
(i) Field trials are required to document time and cost data to provide recommendations and convince regulators, decision-makers, and the general public about the low-cost applicability of microbe-assisted phytoremediation of heavy metal-contaminated sites and for better acceptance in remediation industries.

Conclusively, microbe-assisted phytoremediation technology holds great promise in gaining the sustainable agricultural production in conjunction with phytoremediation of heavy metal-contaminated sites for environmental sustainability.

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References

Adediran GA, Ngwenya BT, Frederick J, Mosselmans W, Heal KV, Harvie BA (2015) Mechanisms behind bacteria induced plant growth promotion and Zn accumulation in Brassica juncea. J Hazard Mater 283:490–499

Afzal M, Khan QM, Sessitsch A (2014) Endophytic bacteria: prospects and applications for the phytoremediation of organic pollutants. Chemosphere 117:232–242

Agostini E, Coniglio MS, Milrad SR, Tigier HA, Giulietti AM (2003) Phytoremediation of 2,4-dichlorophenol by *Brassica napus* hairy root cultures. Biotechnol Appl Biochem 37(2):139–144

Ahemad M, Khan MS (2013) Pesticides as antagonists of rhizobia and the legume- Rhizobium symbiosis: a paradigmatic and mechanistic outlook. Biochem Mol Biol Int 1(4):63–75

Alexander M (1991) Introduction to soil microbiology. Krieger Publishing Company, Malabar

Alford ER, Pilon-Smits EAH, Paschke MW (2010) Metallophytes—a view from the rhizosphere. Plant Soil 337:33–50

Ali H, Khan E (2018) What are heavy metals? Long-standing controversy over the scientific use of the term 'heavy metals' – proposal of a comprehensive definition. Toxicol Environ Chem 100(1):6–19

Ali H, Khan E, Sajad MA (2013) Phytoremediation of heavy metals—concepts and applications. Chemosphere 91:869–881

Antoniadis V, Levizou E, Shaheen SM, Sik OY, Sebastian A, Baum C, Prasad MNV, Wenzel WW, Rinklebe J (2017) Trace elements in the soil-plant interface: Phytoavailability, translocation, and phytoremediation–a review. Earth-Sci Rev 171:621–645

Arshad M, Saleem M, Hussain S (2007) Perspectives of bacterial ACC deaminase in phytoremediation. Trends Biotechnol 25(8):356–362

Arwidsson Z, Johansson E, von Kronhelm T, Allard B, van Hees P (2010) Remediation of metal contaminated soil by organic metabolites from fungi—production of organic acids. Water Air Soil Pollut 205:215–226

Babu AG, Kim JD, Oh BT (2013) Enhancement of heavy metal phytoremediation by Alnus firma with endophytic Bacillus thuringiensis GDB-1. J Hazard Mater 250:477–483

Babu GA, Shea PJ, Sudhakar D, Jung I-B, Byung-Taek O (2015) Potential use of Pseudomonas koreensis AGB-1 in association with Miscanthus sinensis to remediate heavy metal(loid)-contaminated mining site soil. J Environ Manag 151:160–166

Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E, Subramanian S, Smith DL (2018) Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Front Plant Sci 9:1473

Barzanti R, Ozino F, Bazzicalupo M, Gabbrielli R, Galardi F, Gonnelli C, Mengoni A (2007) Isolation and characterization of endophytic bacteria from the nickel hyperaccumulator plant *Alyssum bertolonii*. Microb Ecol 53(2):306–316

Bharagava RN, Chowdhary P, Saxena G (2017) Bioremediation: an ecosustainable green technology: its applications and limitations. In: Bharagava RN (ed) Environmental pollutants and their bioremediation approaches, 1st edn. CRC Press, Boca Raton, pp 1–22. https://doi.org/10.1201/9781315173351-2

Budzikiewicz H (2010) Microbial siderophores. In: Kinghorn AD, Falk H, Kobayashi J (eds) Progress in the chemistry of organic natural products. Springer, Vienna, pp 1–75

Burd GI, Dixon DG, Glick BR (1998) A plant growth-promoting bacterium that decreases nickel toxicity in seedlings. Appl Environ Microbiol 64(10):3663–3668

Burd GI, Dixon DG, Glick BR (2000) Plant growth-promoting bacteria that decrease heavy metal toxicity in plants. Can J Microbiol 46(3):237–245

Cabral L, Soares CFRS, Giachini AJ, Siqueira JO (2015) Arbuscular mycorrhizal fungi in phytoremediation of contaminated areas by trace elements: mechanisms and major benefits of their applications. World J Microbiol Biotechnol 31:1655–1664

Carrillo-Castaneda G, Munoz JJ, Peralta-Videa JR, Gomez E, Gardea- Torresdey JL (2003) Plant growth-promoting bacteria promote copper and iron translocation from root to shoot in alfalfa seedlings. J Plant Nutr 26(9):1801–1814

Chanclud E, Morel J-B (2016) Plant hormones: a fungal point of view. Mol Plant Pathol 17(8):1289–1297

Chandra R, Saxena G, Kumar V (2015) Phytoremediation of environmental pollutants: an ecosustainable green technology to environmental management. In: Chandra R (ed) Advances in biodegradation and bioremediation of industrial waste. CRC Press, Boca Raton, pp 1–30. https://doi.org/10.1201/b18218-2

Chaudhry Q, Blom-Zandstra M, Gupta SK, Joner E (2005) Utilising the synergy between plants and rhizosphere microorganisms to enhance breakdown of organic pollutants in the environment (15 pp). Environ Sci Pollut Res Int 12(1):34–48

Chen YX, Lin Q, Luo YM, He YF, Zhen SJ, Yu YL, Tian GM, Wong MH (2003) The role of citric acid on the phytoremediation of heavy metal contaminated soil. Chemosphere 50(6):807–811

Chen X, Wu C, Tang J, Hu S (2005) Arbuscular mycorrhizae enhance metal lead uptake and growth of host plants under a sand culture experiment. Chemosphere 60(5):665–671

Chen L, Luo S, Xiao X, Guo H, Chen J, Wan Y, Li B, Xu T, Xi Q, Rao C, Liu C, Zeng G (2010) Application of plant growth-promoting endophytes (PGPE) isolated from Solanum nigrum L. for phytoextraction of Cd-polluted soils. Appl Soil Ecol 46(3):383–389

Chen L, Luo S, Li X, Wan Y, Chen J, Liu C (2014) Interaction of Cd hyperaccumulator *Solanum nigrum* L. and functional endophyte *Pseudomonas* sp. Lk9 on soil heavy metals uptake. Soil Biol Biochem 68:300–308

Chirakkara RA, Cameselle C, Reddy KR (2016) Assessing the applicability of phytoremediation of soils with mixed organic and heavy metal contaminants. Rev Environ Sci Biotechnol 15(2):299–326

Coninx L, Martinova V, Rineau F (2017) Chapter Four—Mycorrhiza-assisted phytoremediation. Adv Bot Res 83:127–188

Cornejo P, Meier S, Borie G, Rillig MC, Borie F (2008) Glomalin-related soil protein in a Mediterranean ecosystem affected by a copper smelter and its contribution to Cu and Zn sequestration. Sci Total Environ 406(1–2):154–160

Davies FT, Puryear JD, Newton RJ, Egilla JN, Saraiva Grossi JA (2001) Mycorrhizal fungi enhance accumulation and tolerance of chromium in sunflower (Helianthus annuus). J Plant Physiol 158(6):777–786

Dharni S, Srivastava AK, Samad A, Patra DD (2014) Impact of plant growth promoting Pseudomonas monteilii PsF84 and Pseudomonas plecoglossicid a PsF610 on metal uptake and production of secondary metabolite (monoterpenes) by rose-scented geranium (Pelargonium graveolens cv. bourbon) grown on tannery sludge amended soil. Chemosphere 117:433–439

Dimkpa CO, Svatos A, Dąbrowska P, Schmidt A, Boland W, Kothe E (2008) Involvement of siderophores in the reduction of metal-induced inhibition of auxin synthesis in *Streptomyces* spp. Chemosphere 74(1):19–25

Dixit R, Wasiullah MD, Pandiyan K, Singh UB, Sahu A, Shukla R, Singh BP, Rai JP, Sharma PK, Lade H, Paul D (2015) Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability 7:2189–2212

Egamberdieva D, Abd-Allah EF, Teixeira da Silva JA (2016) Microbially assisted phytoremediation of heavy metal–contaminated soils. In: Ahmad P (ed) Plant metal interaction. Elsevier, Amsterdam, pp 483–498

Elsgaard L, Petersen SO, Debosz K (2001) Effects and risk assessment of linear alkylbenzene sulfonates in agricultural soil. 1. Short-term effects on soil microbiology. Environ Toxicol Chem 20(8):1656–1663

Enyedy EA, Pocsi I, Farkas E (2004) Complexation of desferricoprogen with trivalent Fe, Al, Ga, In and divalent Fe, Ni, Cu, Zn metal ions: effects of the linking chain structure on the metal binding ability of hydroxamate based siderophores. J Inorg Biochem 98(11):1957–1966

Essen SA, Bylund D, Holmstrom SJM, Moberg M, Lundstrom US (2006) Quantification of hydroxamate siderophores in soil solutions of podzolic soil profiles in Sweden. Biometals 19(3):269–282

Farkas E, Batka D, Kremper G, Pocsi I (2008) Structure-based differences between the metal ion selectivity of two siderophores desferrioxamine B (DFB) and desferricoprogen (DFC): why DFC is much better Pb(II) sequestering agent than DFB? J Inorg Biochem 102(8):1654–1659

Filip Z (2002) International approach to assessing soil quality by ecologically-related biological parameters. Agric Ecosyst Environ 88(2):689–712

Fomina MA, Alexander IJ, Colpaert JV, Gadd GM (2005) Solubilization of toxic metal minerals and metal tolerance of mycorrhizal fungi. Soil Biol Biochem 37(5):851–866

Francis AJ, Dodge CJ, Gillow JB (1992) Biodegradation of metal citrate complexes and implications for toxic metal mobility. Nature 356:140–142

Gadd GM (2004) Microorganisms in toxic metal-polluted soils. In: Buscot F, Varma A (eds) Microorganisms in soils: roles in genesis and functions. Springer-Verlag, Berlin, pp 325–358

Gadd GM, Sayer JA (2000) Fungal transformations of metals and metalloids. In: Lovley DR (ed) Environmental microbe-metal interactions. American Society of Microbiology, Washington, pp 237–256

Gamalero E, Glick BR (2012) Plant growth-promoting bacteria and metal phytoremediation. In: Anjum NA, Pereira ME, Ahmad I, Duarte AC, Umar S, Khan NA (eds) Phytotechnologies. Taylor and Francis, Boca Raton, pp 359–374

Giller KE, Witter E, McGrath SP (1998) Toxicity of heavy metals to microorganisms and microbial processes in agricultural soils. Soil Biol Biochem 30(10–11):1389–1414

Gleba D, Borisjuk NV, Borisjuk LG, Kneer R, Poulev A, Skarzhinskaya M, Dushenkov S, Logendra S, Gleba YY, Raskin I (1999) Use of plant roots for phytoremediation and molecular farming. Proc Natl Acad Sci U S A 96(11):5973–5977
Glick BR (2003) Phytoremediation: synergistic use of plants and bacteria to clean up the environment. Biotechnol Adv 21(5):383–393
Glick BR (2005) Modulation of plant ethylene levels by the bacterial enzyme ACC deaminase. FEMS Microbiol Lett 251(1):1–7
Glick BR (2010) Using soil bacteria to facilitate phytoremediation. Biotechnol Adv 28(3):367–374
Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications [online]. Hindawi Publishing Corporation, Scientifica
Glick BR (2014) Bacteria with ACC deaminase can promote plant growth and help to feed the world. Microbiol Res 169(1):30–39
Gomez-Sagasti MT, Marino D (2015) PGPRs and nitrogen-fixing legumes: a perfect team for efficient Cd phytoremediation? Front Plant Sci 6:81
Gonzalez-Chavez MC, Carrillo-Gonzalez R, Wright SF, Nichols KA (2004) The role of glomalin, a protein produced by arbuscular mycorrhizal fungi, in sequestering potentially toxic elements. Environ Pollut 130(3):317–323
Hadi F, Bano A (2010) Effect of diazotrophs (Rhizobium and Azobactor) on growth of maize (Zea mays L.) and accumulation of Lead (Pb) in different plant parts. Pak J Bot 42:4363–4370
Han F, Shan X, Zhang S, Wen B, Owens G (2006) Enhanced cadmium accumulation in maize roots-the impact of organic acids. Plant Soil 289(1–2):355–368
Hao X, Taghavi S, Xie P, Orbach MJ, Alwathnani HA, Rensing C, Wei G (2013) Phytoremediation of heavy and transition metals aided by Legume-Rhizobia symbiosis. Int J Phytoremediation 16(2):179–202
Harvey PJ, Campanella BF, Castro PML, Harms H, Lichtfouse E, Schäffner AR, Smrcek S, Werck-Reichhart D (2002) Phytoremediation of polyaromatic hydrocarbons, anilines and phenols. Environ Sci Pollut Res 9(1):29–47
He CQ, Tan GE, Liang X, Du W, Chen YL, Zhi GY, Zhu Y (2010) Effect of Zn-tolerant bacterial strains on growth and Zn accumulation in Orychophragmus violaceus. Appl Soil Ecol 44(1):1–5
He L, Yang H, Yu Z, Tang J, Xu L, Chen X (2014) Arbuscular mycorrhizal fungal phylogenetic groups differ in affecting host plants along heavy metal levels. J Environ Sci 26:2034–2040
Hrynkiewicz K, Baum C (2012) The potential of rhizosphere microorganisms to promote the plant growth in disturbed soils. In: Malik A, Grohmann E (eds) Environmental protection strategies for sustainable development. Strategies for Sustainability. Springer, Dordrecht, pp 35–64
Islam F, Yasmeen T, Ali Q, Ali S, Arif MS, Hussain S, Rizvi H (2014) Influence of Pseudomonas aeruginosa as PGPR on oxidative stress tolerance in wheat under Zn stress. Ecotoxicol Environ Saf 104:285–293
Iqbal J, Ahemad M (2015) Recent advances in bacteria-assisted phytoremediation of heavy metals from contaminated soil. In: Chandra R (ed) Advances in biodegradation and bioremediation of industrial waste. CRC Press, Boca Raton, pp 401–423
Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Krishnamurthy N (2014) Beeregowda, toxicity, mechanism and health effects of some heavy metals. Interdiscip Toxicol 7(2):60–72
Jia YJ, Ito H, Matsui H, Honma M (2000) 1-Aminocyclopropane-1-carboxylate (ACC) deaminase induced by ACC synthesized and accumulated in *Penicillium citrinum* intracellular spaces. Biosci Biotechnol Biochem 64(2):299–305
Jiang C-y, Sheng X-f, Qian M, Wang Q-y (2008) Isolation and characterization of a heavy metal-resistant Burkholderia sp. from heavy metal-contaminated paddy field soil and its potential in promoting plant growth and heavy metal accumulation in metal-polluted soil. Chemosphere 72(2):157–164
Jing YX, Yan JL, He HD, Yang DJ, Xiao L, Zhong T et al (2014) Characterization of bacteria in the rhizosphere soils of Polygonum pubescens and their potential in promoting growth and Cd, Pb, Zn uptake by Brassica napus. Int J Phytoremediation 16:321–333

Joner E, Briones R, Leyval C (2000) Metal-binding capacity of arbuscular mycorrhizal mycelium. Plant Soil 226:227–234

Jones DL (1998) Organic acids in the rhizosphere–a critical review. Plant Soil 205(1):25–44

Khan MS, Zaidi A, Wani PA, Oves M (2009) Role of plant growth promoting rhizobacteria in the remediation of metal contaminated soils. Environ Chem Lett 7(1):1–19

Khan A, Sharif M, Ali A, Shah SNM, Mian IA, Wahid F, Jan B, Adnan M, Nawaz S, Ali N (2014) Potential of AM fungi in phytoremediation of heavy metals and effect on yield of wheat crop. Am J Plant Sci 5:1578–1586

Kuffner M, De Maria S, Puschenreiter M, Fallmann K, Wieshammer G, Gorfer M, Strauss J, Rivelli AR, Sessitsch A (2010) Culturable bacteria from Zn- and Cd-accumulating with differential effects on plant growth and heavy metal availability. J Appl Microbiol 108(4):1471–1484

Lee JH (2013) An overview of phytoremediation as a potentially promising technology for environmental pollution control. Biotechnol Bioprocess Eng 18(3):431–439

Li WC, Ye ZH, Wong MH (2010) Metal mobilization and production of short chain organic acids by rhizosphere bacteria associated with a Cd/Zn hyperaccumulating plant *Sedum alfredii*. Plant Soil 326(1–2):453–467

Li HY, Wie DQ, Shen M, Zhou ZP (2012) Endophytes and their role in phytoremediation. Fungal Divers 54(1):11–18

Li X, Li D, Yana Z, Ao Y (2018) Biosorption and bioaccumulation characteristics of cadmium by plant growth-promoting rhizobacteria. RSC Adv 8:30902–30911

Liang X, Chi-Quan HE, Gang NI, Tang G-E, Chen X-P, Lei Y-R (2014) Growth and Cd accumulation of Orychophragmus violaceus as affected by inoculation of Cd-tolerant bacterial Strains. Pedosphere 24(3):322–329

Lodewyckx C, Taghavi S, Mergeay M, Vangronsveld J, Clijsters H, van der Lelie D (2001) The effect of recombinant heavy metal-resistant endophytic bacteria on heavy metal uptake by their host plant. Int J Phytoremediation 3(2):173–187

Long X, Chen X, Chen Y, Wong Jonathan W-C, Wei Z, Wu Q (2011) Isolation and characterization endophytic bacteria from hyperaccumulator Sedum alfredii Hance and their potential to promote phytoextraction of zinc polluted soil. World J Microbiol Biotechnol 27(5):1197–1207

Luo S, Chen L, Chen J, Xiao X, Xu T, Wan Y, Rao C, Liu C, Liu Y, Lai C, Zeng G (2011) Analysis and characterization of cultivable heavy metal-resistant bacterial endophytes isolated from Cd hyperaccumulator *Solanum nigrum* L. and their potential use for phytoremediation. Chemosphere 85:1130–1138

Ma Y, Prasad MNV, Rajkumar M, Freitas H (2011) Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils. Biotechnol Adv 29:248–258

Ma Y, Rajkumar M, Freitas H (2009) Inoculation of plant growth promoting bacterium Achromobacter xylosoxidans strain Ax10 for the improvement of copper phytoextraction by Brassica juncea. J Environ Manag 90(2):831–837

Ma Y, Rajkumar M, Luo Y, Freitas H (2013) Phytoextraction of heavy metal polluted soils using Sedum plumbizincicola inoculated with metal mobilizing Phyllobacterium myrsinacearum RC6b. Chemosphere 93(7):1386–1392

Ma Y, Oliviera RS, Nai F, Rajkumar M, Luo Y, Rocha I, Freitas H (2015) The hyperaccumulator Sedum plumbizincicola harbors metal-resistant endophytic bacteria that improve its phytoextraction capacity in multi-metal contaminated soil. J Environ Manag 156:62–69

Ma Y, Rajkumar M, Zhang C, Freitas H (2016a) Inoculation of Brassica oxyrrhina with plant growth promoting bacteria for the improvement of heavy metal phytoremediation under drought conditions. J Hazard Mater 320:36–44

Ma Y, Oliveira RS, Freitas H, Zhang C (2016b) Biochemical and molecular mechanisms of plant microbe-metal interactions: relevance for phytoremediation. Front Plant Sci 7:918

Madhaiyan M, Poonguzhali S, Sa T (2007) Metal tolerating methylotrophic bacteria reduces nickel and cadmium toxicity and promotes plant growth of tomato (Lycopersicon esculentum L.). Chemosphere 69(2):220–228

Mahar A, Wang P, Ali A, Awasthi MK, Lahori AH, Wang Q, Li R, Zhang Z (2016) Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: a review. Ecotoxicol Environ Saf 126:111–121

Marques APGC, Rangel AOSS, Castro PML (2009) Remediation of heavy metal contaminated soils: phytoremediation as a potentially promising clean-up technology. Crit Rev Environ Sci Technol 39:622–654

Martino E, Perotto S, Parsons R, Gadd GM (2003) Solubilization of insoluble inorganic zinc compounds by ericoid mycorrhizal fungi derived from heavy metal polluted sites. Soil Biol Biochem 35(1):133–141

Maszenan AM, Liu Y, Ng WJ (2011) Bioremediation of wastewaters with recalcitrant organic compounds and metals by aerobic granules. Biotechnol Adv 29(1):111–123

Mathew DC, Ho Y-N, Gicana RG, Mathew GM, Chien M-C, Huang C-C, Chauvat F (2015) A rhizosphere-associated symbiont, Photobacterium spp. strain MELD1, and Its targeted synergistic activity for phytoprotection against mercury. PLoS One 10(3):e0121178

Mayak S, Tirosh T, Glick BR (2004) Plant growth-promoting bacteria confer resistance in tomato plants to salt stress. Plant Physiol Biochem 42(6):565–572

Meier S, Borie F, Bolan N, Cornejo P (2012) Phytoremediation of metal-polluted soils by arbuscular mycorrhizal fungi. Crit Rev Environ Sci Technol 42(7):741–775

Mendes G, Freitas ALM, Pereira OL, da Silva IR, Vassilev NB, Costa MD (2014) Mechanisms of phosphate solubilization by fungal isolates when exposed to different P sources. Ann Microbiol 64(1):239–249

Miethke M, Marahiel MA (2007) Siderophore-based iron acquisition and pathogen control. Microbiol Mol Biol R 71(3):413–451

Mudhoo A, Sharma SK, Lin ZQ, Dhankher OP (2010) Phytoremediation of arsenic-contaminated environment an overview. In: Sharma A, Mudhoo SK (eds) Green chemistry for environmental sustainability, vol 127. Taylor and Francis Group, Boca Ratan

Mukherjee G, Saha C, Naskar N, Mukherjee A, Mukherjee A, Lahiri S, Majumder AL, Seal A (2018) An endophytic bacterial consortium modulates multiple strategies to improve arsenic phytoremediation efficacy in Solanum nigrum. Sci Rep 8(1):1–16

Mukhopadhyay S, Maiti SK (2010) Phytoremediation of metal mine waste. Appl Ecol Environ Res 8:207–222

Muthusaravanan S, Sivarajasekar N, Vivek JS, Paramasivan T, Naushad M, Prakashmaran J, Gayathri V, Al-Duaij OK (2018) Phytoremediation of heavy metals: mechanisms, methods and enhancements. Environ Chem Lett 16(4):1339–1359

Nagajyoti PC, Lee KD, Sreekanth TVM (2010a) Heavy metals, occurrence and toxicity for plants: a review. Environ Chem Lett 8:199–216

Nagajyoti PC, Sreekanth TVM, Lee KD (2010b) Heavy metals, occurrence and toxicity for plants: a review. Environ Chem Lett 8(3):199–216

Nagata S, Yamaji K, Nomura N, Ishimoto H (2015) Root endophytes enhance stress-tolerance of L. growing in a mining pond of eastern Japan. Plant Species Biol 30(2):116–125

Nautiyal CS, Bhadauria S, Kumar P, Lal H, Mondal R, Verma D (2000) Stress induced phosphate solubilization in bacteria isolated from alkaline soils. FEMS Microbiol Lett 182(2):291–296

Ouzounidou G, Moustakas M, Symeonidis L, Karataglis S (2006) Response of wheat seedlings to Ni stress: effects of supplemental calcium. Arch Environ Contam Toxicol 50(3):346–352

Ozyigit II, Dogan I (2015) Plant–microbe interactions in phytoremediation. https://doi.org/10.1016/B978-0-12-799937-1.00009-7

Panfili F, Schneider A, Vives A, Perrot F, Hubert P, Pellerin S (2009) Cadmium uptake by durum wheat in presence of citrate. Plant Soil 316(1):299–309

Panhwar QA, Jusop S, Naher UA, Othman R, Razi MI (2013) Application of potential phosphate-solubilizing bacteria and organic acids on phosphate solubilization from phosphate rock in aerobic rice. Sci World J 2013:272409

Parida BK, Chhibba IM, Nayyar VK (2003) Influence of nickel contaminated soils on fenugreek (*Trigonella corniculata* L.) growth and mineral composition. Sci Hortic-Amsterdam 98(2):113–119

Ping L, Boland W (2004) Signals from the underground: bacterial volatiles promote growth in *Arabidopsis*. Trends Plant Sci 9(6):263–266

Pluhacek T, Lemr K, Ghosh D, Milde D, Novak J, Havlicek V (2016) Characterization of microbial siderophores by mass spectrometry. Mass Spectrom Rev 35(1):35–47

Pocsi I (2011) Toxic metal/metalloid tolerance in fungi—a biotechnology-oriented approach. In: Banfalvi G (ed) Cellular effects of heavy metals. Springer, Berlin, pp 31–58

Rajkumar M, Ae N, Freitas H (2009) Endophytic bacteria and their potential to enhance heavy metal phytoextraction. Chemosphere 77(2):153–160

Rajkumar M, Ae N, Prasad MNV, Freitas H (2010) Potential of siderophore producing bacteria for improving heavy metal phytoextraction. Trends Biotechnol 28(3):142–149

Rajkumar M, Sandhya S, Prasad MNV, Freitas H (2012) Perspectives of plant associated microbes in heavy metal phytoremediation. Biotechnol Adv 30(6):1562–1574

Rawlings DE (1997) Mesophilic, autotrophic bioleaching bacteria: description, physiology and role. In: Rawlings DE (ed) Biomining: theory, microbes and industrial processes. Springer, Berlin, Heidelberg, Germany, pp 229–245

Rawlings DE, Silver S (1995) Mining with microbes. Biotech 13:773–738

Saha R, Saha N, Donofrio RS, Bestervelt LL (2013) Microbial siderophores: a mini review. J Basic Microbiol 53(4):303–317

Saravanan VS, Madhaiyan M, Thangaraju M (2007) Solubilization 1447 of zinc compounds by the diazotrophic, plant growth promoting bacterium *Gluconacetobacter diazotrophicus*. Chemosphere 66(9):1794–1798

Sarwar N, Imran M, Shaheen MR, Ishaq W, Kamran A, Matloob A, Rehim A, Hussain S (2017) Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. Chemosphere 171:710–721

Saxena G, Bharagava RN (2017) Organic and inorganic pollutants in industrial wastes, their ecotoxicological effects, health hazards and bioremediation approaches. In: Bharagava RN (ed) Environmental pollutants and their bioremediation approaches, 1st edn. CRC Press, Boca Raton, pp 23–56

Schalk IJ, Hannauer M, Braud A (2011) New roles for bacterial siderophores in metal transport and tolerance. Environ Microbiol 13(11):2844–2854

Schippers A, Sand W (1999) Bacterial leaching of metal sulfides proceeds by two indirect mechanisms via thiosulfate or via polysulfides and sulfur. Appl Environ Microbiol 65(1):319–321

Sheng X-F, Xia J-J, Jiang C-Y, He L-Y, Qian M (2008) Characterization of heavy metal-resistant endophytic bacteria from rape (Brassica napus) roots and their potential in promoting the growth and lead accumulation of rape. Environ Pollut 156(3):1164–1170

Shi W, Becker J, Bischoff M, Turco RF, Konopka AE (2002) Association of microbial community composition and activity with lead, chromium, and hydrocarbon contamination. Appl Environ Microbiol 68(8):3859–3866

Shi JY, Lin HR, Yuan XF, Chen XC, Shen CF, Chen YX (2011) Enhancement of copper availability and microbial community changes in rice rhizospheres affected by sulfur. Molecules 16:1409–1417

Shin M-N, Shim J, You Y, Myung H, Bang K-S, Cho M, Kamala-Kannan S, Byung-Taek O (2012) Characterization of lead resistant endophytic Bacillus sp. MN3-4 and its potential for promoting lead accumulation in metal hyperaccumulator Alnus firma. J Hazard Mater 199-200:314–320

Sreelal G, Jayanthi R (2017) Review on phytoremediation technology for removal of soil contaminant. Indian J Sci Res 14:127–130

Srivastava S, Singh N (2014) Mitigation approach of arsenic toxicity in chickpea grown in arsenic amended soil with arsenic tolerant plant growth promoting Acinetobacter sp. Ecol Eng 70:146–153

Srivastava S, Verma PC, Chaudhry V, Namrata S, Abhilash PC, Kumar KV, Sharma N, Singh N (2013) Influence of inoculation of arsenic-resistant Staphylococcus arlettae on growth and arsenic uptake in Brassica juncea (L.) Czern. Var. R-46. J Hazard Mater 262:1039–1047

Sun L-N, Zhang Y-F, He L-Y, Chen Z-J, Wang Q-Y, Qian M, Sheng X-F (2010) Genetic diversity and characterization of heavy metal-resistant-endophytic bacteria from two copper-tolerant plant species on copper mine wasteland. Bioresour Technol 101(2):501–509

Tiwari S, Singh SN, Garg SK (2012) Stimulated phytoextraction of metals from fly ash by microbial interventions. Environ Technol 33(21):2405–2413

Ullah A, Heng S, Munis MFH, Fahad S, Yang X (2015) Phytoremediation of heavy metals assisted by plant growth promoting (PGP) bacteria: a review. Environ Exp Bot 117:28–40

van der Hiejden MGA, Bardgett RD, van Straalen NM (2008) The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol Lett 11(3):296–310

Vangronsveld J, Herzig R, Weyens N, Boulet J, Adriaensen K, Ruttens A et al (2009) Phytoremediation of contaminated soils and groundwater: lessons from the field. Environ Sci Pollut Res 16:765–794

Visioli G, D'Egidio S, Vamerali T, Mattarozzi M, Sanangelantoni AM (2014) Culturable endophytic bacteria enhance Ni translocation in the hyperaccumulator Noccaea caerulescens. Chemosphere 117:538–544

Viterbo A, Landau U, Kim S, Chernin L, Chet I (2010) Characterization of ACC deaminase from the biocontrol and plant growth-promoting agent *Trichoderma asperellum* T203. FEMS Microbiol Lett 305(1):42–48

Vivas A, Biro B, Nemeth T, Barea J, Azcon R (2006) Nickel-tolerant Brevibacillus brevis and arbuscular mycorrhizal fungus can reduce metal acquisition and nickel toxicity effects in plant growing in nickel supplemented soil. Soil Biol Biochem 38(9):2694–2704

Vodnik D, Grčman H, Maček I, van Elteren JT, Kovǎcevič M (2008) The contribution of glomalin related soil protein to Pb and Zn sequestration in polluted soil. Sci Total Environ 392:130–136

Wan Y, Luo S, Chen J, Xiao X, Liang C, Zeng G, Liu C, He Y (2012) Effect of endophyte-infection on growth parameters and Cd-induced phytotoxicity of Cd-hyperaccumulator Solanum nigrum L. Chemosphere 89(6):743–750

Wang W, Qiu Z, Tan H, Cao L (2014) Siderophore production by actinobacteria. Biometals 27(4):623–631

Wenzel WW (2008) Rhizosphere processes and management in plant-assisted bioremediation (phytoremediation) of soils. Plant Soil 321(1–2):385–408

Wu CH, Wood TK, Mulchandani A, Chen W (2006) Engineering Plant-Microbe symbiosis for rhizoremediation of heavy metals. Appl Environ Microbiol 72(2):1129–1134

Yadav SK (2010) Heavy metals toxicity in plants: an overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants. S Afr J Bot 76(2):167–117

Yuan M, He H, Xiao L, Zhong T, Liu H, Li S, Deng P, Ye Z, Jing Y (2013) Enhancement of Cd phytoextraction by two Amaranthus species with endophytic Rahnella sp. JN27. Chemosphere 103:99–104

Yuan M, He H, Xiao L, Zhong T, Liu H, Li S, Deng P, Ye Z, Jing Y (2014) Enhancement of Cd phytoextraction by two Amaranthus species with endophytic Rahnella sp. JN27. Chemosphere 103:99–104

Zhang Y-f, He L-y, Chen Z-j, Wang Q-y, Qian M, Sheng X-f (2011) Characterization of ACC deaminase-producing endophytic bacteria isolated from copper-tolerant plants and their potential in promoting the growth and copper accumulation of Brassica napus. Chemosphere 83(1):57–62

Zhang X, Lin L, Zhu Z, Yang X, Wang Y, An Q (2013) Colonization and modulation of host growth and metal uptake by endophytic bacteria of Sedum alfredii. Int J Phytoremediation 15(1):51–64

Zhu L-J, Guan D-X, Luo J, Rathinasabapathi B, Ma LQ (2014) Characterization of arsenic-resistant endophytic bacteria from hyperaccumulators Pteris vittata and Pteris multifida. Chemosphere 113:9–16

Złoch M, Thiem D, Gadzała-Kopciuch R, Hrynkiewicz K (2016) Synthesis of siderophores by plant-associated metallotolerant bacteria under exposure to Cd^{2+}. Chemosphere 156:312–325
Złoch M, Kowalkowski T, Tyburski J, Hrynkiewicz K (2017) Modeling of phytoextraction efficiency of microbially stimulated *Salix dasyclados* L. Int J Phytoremediation 19(12):1150–1164